Methodologies for improving product development phases through PLM

by

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Introduction

1.1 Background

Product manufacturing industries have evolved from single, co-located factories into vast interlinked enterprises with several stakeholders and globally distributed supply chains. Products are now being sold in widely varying markets around the world. At the same time, increasing competition has put additional pressure on the manufacturers to develop new and innovative products in the shortest possible times. As a result, product designs are becoming increasingly complex. Developing such complex products requires a high degree of coordination and collaboration between the various stakeholders of the enterprise, as well as techniques to assimilate all information and facilitate decision making. These requirements have fostered the creation of a Product Lifecycle Management (PLM) framework to manage activities across the enterprise.

1.1.1 Product Lifecycle Management

Computer-based tools are widely used in the manufacturing industry for engineering activities (such as geometric modeling, kinematic and dynamic analysis, and

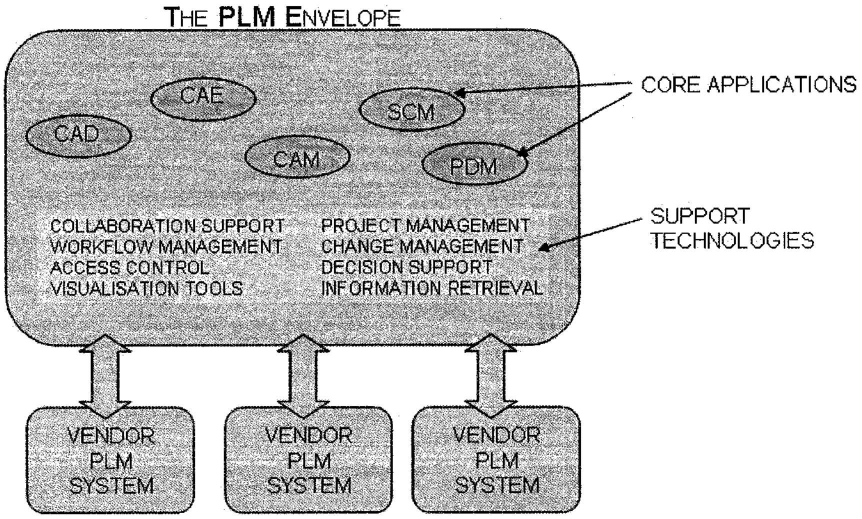


Figure 1.1: Conceptual framework of present PLM systems

process planning) as well as other support activities (such as requirements planning, inventory control, and supply chain management). However, only recently has there been an emphasis on a unified approach to all the activities of a large production enterprise. The overall idea is to utilize emerging software technologies in knowledge management, data translation, web-based collaboration, etc., to facilitate innovation by allowing faster and effective information exchange, use of past knowledge, and seamless collaboration between various functions of the enterprise. This has led to a grand vision of a Product Lifecycle Management (PLM) framework, which will streamline activities ranging from product design and definition, planning, management and control of production tasks, right up to end-of-life treatment, and decommissioning of the product. PLM has been defined as a strategy that provides a structured framework to facilitate collaboration both internally and externally among strategic partners throughout a product's life cycle from initial concept and design through operation, maintenance and retirement [2].

Commercial software vendors have already started offering PLM solutions that can be customized and implemented for a given enterprise. The evolving architecture of such PLM solutions is shown in Figure 1.1. At the core, are traditional applications for creating product information such as CAD (Computer Aided Design), FEA (Finite Element Analysis), CAM (Computer Aided Manufacturing), BOM (Bill of Material) management, SCM (Supply Chain Management), etc. These applications are enclosed in an envelope of support software and technologies, which provide common data storage, collaboration and information exchange capabilities, context-based information retrieval, configuration management, data security and access management, etc. In effect, the PLM envelope acts as the interface between different applications, as well as between various departments of the manufacturer and its vendors. The aim is to automate the capture of product related knowledge and information created by all the different functions of enterprise and share it with the right people, at the right time, and in the right context; thus enabling correct and efficient decision making [3].

Current PLM solutions significantly improve the traditional tools for design and production management in a manufacturing enterprise. However, such an integrated, collaborative PLM framework also generates a pool of information that can potentially be used to support other decision making activities, which have hitherto relied completely on human experience and expertise.

One burning concern for product manufacturers that currently relies heavily on human experience and expertise, is the fulfillment of requirements arising from regulations governing hazardous substances in products and requirements on proper treatment of products at the end of their useful lives. These regulations are often referred to as regulations for Extended Producer Responsibility.

1.1.2 Regulations for Extended Producer Responsibility

The use of manufactured goods, be it cars, computers, or cell phones, has increased considerably in the last few decades. Certain products, such as cars or refrigerators, are sometimes collected at junkyards, which scavenge components to be refurbished and reused, or metallic parts for recycling. However, several tonnes of waste from used and damaged products is disposed every year along with municipal waste. Adequate processing of these "end-of-life" products puts immense pressure on the civic authorities. This is especially true in European and Asian countries where the waste generated is increasing, but the space available for landfills and incinerators is receding. Many of these products contain substances such as lead, cadmium, etc., which are considered harmful in case of exposure to humans or detrimental to the environment. Many materials currently used in consumer products are not recyclable. Moreover, different material combinations and product structures (e.g., embedded smart chips in printer toner cartridges), as well as the variety of products in municipal waste makes it highly uneconomical, and often impossible, to recycle them.

The popular solution that has emerged among authorities all over the world is to transfer the responsibility of dealing with end-of-life products back to the product manufacturers. Extended Producer Responsibility laws (or Product take-back laws) have already been enacted in Japan, Germany and certain other European countries. The European Union has passed directives that would require all member states to enact similar laws [4, 5, 6]. In the US, solid waste arising from disposal of products is governed by the Resource Conservation and Recovery Act (RCRA) in the Code of Federal Regulations [7]. While the actual regulations differ depending upon the country and the product category, they usually include the following three types of clauses:

1. bans or restrictions on the use of certain substances,
2. stringent requirements on amounts of material to be recovered and recycled from end-of-life products, and
3. transfer of financial, and in some cases operational, responsibility of collection and treatment of end-of-life products onto the Original Equipment Manufacturer (OEM).

1.2 Issues faced during product development

The Extended Producer Responsibility regulations, combined with stringent existing regulations on proper disposal of materials and substances, place a substantial financial and operational burden on the OEMs. The American electronics industry estimates that increased material costs, for compliance with the directive on Waste Electrical and Electronic Equipment (WEEE) [8], will run from \$140 to \$900 million, and additional infrastructure, materials evaluation and qualification costs will likely run into tens of billions [9]. On the other hand, non-compliance can cost millions in terms of fines and loss of markets. In a separate report, analysts estimate that requirements of the ELV directive [4] might result in an additional €20 to €150 per vehicle in costs for compliance [10].

In addition, close coordination is required between OEMs, suppliers, maintenance facilities and treatment facilities, to ensure compliance at various stages in the life-cycle of the product. Under the present practices, problems often arise due to the variations in controlled substance lists and thresholds in different countries, various special cases and exceptions in the regulations, multiple reporting formats, etc. Insufficient knowledge about costs and performance of alternative materials, technologies, or parts that can be procured also contribute to problems. Suppliers are faced with disparate requirements from different OEMs, late changes in specifications, excessively stringent specifications, absence of mechanisms to provide feedback to OEMs, etc. Delays and expensive modifications are often encountered due to late detection of non-compliant parts, or implementation of design changes without sufficient evaluation. Planned end-of-life treatment procedures are often hindered by unavailability of tools and equipment at ATFs, or reduced demand for recycled/refurbished goods, etc.

In order to alleviate these problems, we identified the important capabilities required in different phases of the product development cycle, as discussed below:

1. **Conceptual and embodiment design phase**

   The configuration of a new product model, along with the properties, materials and processing of the components involved, is decided in the conceptual design and embodiment design phases. Consequently, right from these early stages, OEMs need to account for compliance with hazardous substance regulations and recyclability requirements. Modern consumer products are complex assemblies of parts and components, some of which are built in-house by the OEM, while others are procured from external suppliers. Detailed design of each component is often carried out separately by the individual suppliers. As discussed earlier, the nature of the regulations depends on the substance being controlled, the application where it is used, the industry, and even varies between different countries. The regulations may apply to the entire product or portions of the product, e.g., the battery, or all plastic parts, or all paints and coatings. It is the OEM's responsibility to ensure that the product and its components conform to all regulations applicable in the market where the product is to be sold.

At present, OEMs often uniformly specify stringent substance content limits or recyclable content requirements for all components in the product. They seldom consider the producability, expected costs and performance of the component that has to be manufactured to these stringent specifications. This places undue pressure on suppliers of some of the components resulting in the increase in production costs or a drop in the quality of the product. Often, costly design changes have to be made if a violation, technical infeasibility or unacceptable loss of quality is detected in the later development stages.

Therefore, there is a need to intelligently devise specifications for individual components so as to obtain the best performance from the product without escalation of costs or violation of regulations. At the same time, it should be noted that before detailed design is completed, the performance, production cost, etc., of a component cannot be accurately known. Thus, any method to devise specifications should adequately account for the inherent uncertainty in estimating properties of components.

2. **Detailed design and production phase**

   Once detailed design of the components is completed, the material and substance content in each part needs to be tracked to ensure that the resultant end product is compliant. Commercial PLM solutions provide modules for detailed documentation and tracking of amounts of regulated substances contained in components, and for analyzing the compliance of each component as well as the final product. During this stage, changes to the product design may be necessitated if a violation of regulations is detected. Design changes are also required if technical infeasibilities or high costs are observed during detailed design or production of a component. Sometimes, such changes may be required to meet new or revised regulations, or to incorporate advanced materials or technologies.

   In all such cases, engineering changes (ECs) have to be suggested to overcome the problem. Such ECs usually have cascading effects on various other parts and processes of the product. These effects have to be carefully studied with respect to their engineering and business impacts. Current Engineering

Change Management (ECM) software and modules employ the industry standard CM II (Configuration Management II) closed-loop change management system. Comprehensive evaluations of a proposed change under this system, referred to as the standard-track evaluation process, is very time consuming and requires fair amount of experience and expertise on the part of the user. Since the aforementioned changes are already encountered late in the design cycle, speed of processing is extremely important to ensure minimal loss of production. Consequently, many of these changes are processed through a less rigorous fast-track process, where there is a risk of overlooking important impacts that might cause delays or require expensive modifications.

Therefore, there is a need for a change evaluation process that is expeditious, but at the same time comprehensive and less dependent on the expertise of the user.

3. Planning of end-of-life treatment strategy

As mentioned earlier, the financial burden of proper treatment of end-of-life products is now being placed on the OEMs. Consequently, it is important for the OEMs to plan the treatment process. This will enable OEMs to optimize on the treatment costs and also preempt any bottlenecks or expensive activities, which can then be avoided by appropriate design changes. Planning the treatment process involves determination of the extent to which the parts of the product are to be separated and the end-fate (recycling/reuse/disposal) of each separated part.

While deciding the end-of-life treatment strategy OEMs must account for applicable regulations on recovery and disposal, available technology to separate components and materials, available technology for recycling materials, the costs for disassembly and processing, etc. In addition, local and temporal factors, such as the proximity of disposal sites or recycling facilities, damage and wear on components in the incoming end-of-life product, and the prevailing market for refurbished components may also affect the profitability of a preselected treatment plan. Methods discussed in research literature to assist end-of-life treatment planning are not able to accommodate these factors that can vary for each incoming product. Moreover these methods require specialized representations of the product assembly, containing information about joints between components, precedence relationships between joint separation operations, etc. These representations often have to be built manually, wherein considerable time is wasted in redefining the product.

Thus, there is a need for a systematic method to dynamically plan the optimal treatment strategy for incoming end-of-life products on a case-by-case basis. Any such method needs to be integrated with the commonly used product data representations, such as CAD models. This will require automated identification of joints from CAD models and inferring additional information, such as size and orientation of the joint, tool and accessibility requirements for joint separation, etc.

1.3 Thesis Problem

The goal of this research is to develop techniques that use the advantages provided by the PLM framework to address the issues identified in different phases of product development.

Based on the issues identified in the previous section, we define three research problems that will be addressed in this thesis. They are:

1. *Selection of regulated substance content specifications for product components*: To develop a method to decide substance content specifications for product components in the early design phase, so as to maximize overall product performance. The method should avoid unfair pressure on design of some components or inordinate increase in production costs, without violating any substance regulations applicable to the product. The method should also account for uncertainty in estimation of component properties in the early design phase.
2. *Development of a decision support system for evaluating impacts of Engineering Changes*: To develop a decision support system to facilitate evaluation of impacts of ECs arising from end-of-life product considerations. The system should use existing industry specific knowledge and experience from previously implemented ECs to assist the evaluation process.
3. *Identification and characterization of joints in CAD assembly models for end-of-life treatment planning*: To develop a framework that allows dynamic, case-by-case planning of end-of-life treatment for incoming end-of-life products, and

to develop a method for identification of joints from CAD assembly models of the product and characterize them in order to determine conditions for disengagement.

1.4 Thesis Outline

This chapter discussed the nature product end-of-life regulations, and the potential for OEMs to better manage their responsibilities using the Product Lifecycle Management framework. It also identified three important issues faced by OEMs which form the focus of this research. The remainder of this research proposal is organized as follows:

Chapter II addresses in detail the problem of selecting optimal specifications, while accounting for substance regulations and recyclability requirements. It develops a framework for deciding substance content specifications during the design embodiment stage. The use of chance constrained programming to account for uncertainties about the properties of component alternatives at this early design stage is demonstrated.

Chapter III explains in detail a decision support system that uses dynamic workflows for evaluation of impacts of ECs. It also discusses methods to use experience obtained from previously studied engineering changes to facilitate the evaluation process.

Chapter IV explains the envisaged framework for dynamic, case-by-case planning of end-of-life treatment processes. It further discusses the proposed algorithms for identification and characterization of joints in CAD assembly models.

Chapter V summarizes the research tasks and discusses the expected academic and industrial contributions of this work. It also includes a discussion about the limitations of the present work and avenues for future research.

CHAPTER II

Selection of regulated substance content specifications for product components

As discussed in chapter I, there is a need for OEMs to intelligently select regulated substance content specifications for the components comprising the product. This chapter explains the approach developed in this research to enable the same.

2.1 Motivation

Emerging regulations place restrictions on amounts of hazardous or harmful substances contained in manufactured products placed on the market. Laws also specify minimum amounts of the product that must be recovered and recycled. Restrictions vary from total bans or phase-outs for certain substances (e.g., Azo-dyes, CFCs, lead, mercury, etc.) to limits specifying allowable amounts of certain substances (e.g., benzene, halogenated flame retardants, etc.) in a product. The limits may be specified for a product or a sub-assembly of the product, or directly on a single homogeneous component. Limits are often expressed in terms of a percentage of the total weight of the product or sub-assembly. However, some clauses specify limits on the absolute weight of the substance per product. Special considerations or clauses are also included to allow exceptions or variation in the limits for certain applications (e.g., hexavalent chromium in corrosion resistant coatings) or components (e.g., lead in batteries). Studies are being carried out on harmful effects of a number of substances, in addition to the substances already regulated, and a broader range of substances is expected to be regulated in future.

The regulations place the responsibility of ensuring compliance on the Original Equipment Manufacturer (OEM) of the product. Consequently, OEMs have started monitoring and documenting amounts of substances in each component of their products [11, 12], whether built in-house or procured from their suppliers. However, merely monitoring amounts of substances is not sufficient. Any violation of regulations detected at this stage undoubtedly leads to costly changes and delays in time-to-market. Since detail design of components and processes has been completed, the emphasis is on making minimal changes in order to achieve compliance. The resulting configuration is seldom optimal.

OEMs often specify their own, stringent limits on amounts of regulated substances in all supplied (and in-house) components. These limits are applied uniformly to all components usually as a percentage of the weight of the component. Often, the effect of such blanket specifications on the cost or quality of individual components, or the technical feasibility of meeting other functional requirements, is not completely understood. Neither do the suppliers get adequate opportunity to give feedback to the OEMs on these issues. This often puts undue pressure on suppliers of certain components, making it difficult or expensive to meet all required specifications. Moreover, opportunities to improve overall performance of the product by reducing restrictions on critical components (at the expense of non-critical components) may be lost.

In today's competitive environment, it is important for OEMs to be the first to bring new, innovative, and high quality products to the market. Therefore, it is important reduce redesign iterations. However, product configurations and specifications for components in the configuration are decided early in the design process. Before detailed design of components has been completed, it is difficult to predict the exact amounts of hazardous substances, production costs, performance, etc., for any component designed to prescribed specifications. Thus, there is a need for a systematic method for OEMs to select optimal substance content specifications, while taking into account the uncertainty in the information available at the early design stage.

2.2 Objective

The objective of this research phase is to develop a method to decide substance content specifications for product components in the early design phase, so as to maximize overall product performance without violating any substance regulations applicable to the product. We divide the research into the following major tasks:

- Development of a framework for evaluating alternative specifications for components and selection of the optimal set of specifications
- Modeling of the optimization step to adequately account for uncertainty in information about component alternatives

- Development of an algorithm to solve the resulting formulation

2.3 Literature Review

The design of new products can be broadly classified into three stages: conceptual design, embodiment design, and detail design [13]. Decisions about material and processing specifications for components, such as heat treatments or surface coatings, as well as performance requirements are made in the embodiment design stage. Since hazardous substances contained in a component are implicitly dependent on these requirements, the corresponding limits should also be decided at the same time.

To the best of our knowledge, the selection of hazardous substance and recyclable content specifications for components, in the embodiment design stage, has not been previously studied in literature. However, some methods to incorporate other considerations during embodiment design have been discussed. Vairaktarakis [14] presents a method for obtaining the optimal parts mix for a product, given alternative choices for each part, subject to budgetary constraints. The importance of individual parts in the overall product, as well as performance ratings for each alternative choice, are calculated using house of quality matrices in a QFD (Quality Function Deployment [15]) style approach. Subsequently, a linear programming problem is formulated to select the optimal parts mix. Kuppuraju, et al. [16] present a technique that involves creation of alternative concepts, selection of most-likely-to-succeed concepts, and formulation of selection-decision-support problems to rank feasible alternatives in order of preference. The method concentrates only on quantifying and comparing desirable attributes to decide relative rank, and does not account for quantitative requirements or constraints. Moreover, both the methods mentioned above assume detailed and accurate knowledge is available for all alternative design concepts.

As in the case of selection of regulated substance specifications, uncertainty about input variables is encountered in a number of practical engineering problems. Such uncertainty is often sought to be wiped out using mean or expected values. However, this may lead to a high probability that the solution obtained will be infeasible. The other approach is to look for a conservative solution, i.e., one that is feasible in all possible cases. Such a solution, often called a "fat solution," reflects total risk aversion on the part of the decision maker, and is often very expensive [17]. In order to overcome these issues, different approaches (e.g., reliability analysis, robust optimization, stochastic programming, etc.) have been suggested to tackle uncertainty in different domains of decision-making problems.

Chance constrained programming [18], a class of stochastic programming, is often the most suitable approach for single step decision problems, where it is difficult to quantify the costs of corrective actions or penalties faced if the solution obtained is infeasible. Constraint equations are modeled such that the coefficients of the decision variables have known probability distributions. For each constraint, the user can specify the probability with which the constraint must be satisfied, or correspondingly, the acceptable risk of the constraint being violated. This approach is suitable for the embodiment design stage, where properties of component alternatives, such as costs, weight, surface area to be coated, etc., can be estimated in terms of probability distributions.

There does not exist a unique solver for chance constrained programs [18]. The choice of solver depends on how random and decision variables interact in the constraint model. However, techniques involving conversion to an equivalent deterministic form [19, 20], branch and bound methods [21], and supporting hyperplane methods [22] have been previously used to solve certain chance constrained formulations.

2.4 Framework for selection of regulated substance content specifications for product components

Traditionally, the conceptual and embodiment design phases are carried out inhouse by a core team of designers at the OEM. Considerable experience and knowledge about production of individual components is required from these designers in order to prescribe the material and processing specifications for each component in the chosen design configuration. Restrictions on regulated substances contained in each component also need to be specified at this time. However, it is unreasonable to expect the designers to know intricacies, such as regulated substance contents, or recyclable material content, etc., for various alternative methods of making a component. Such information should ideally be obtained from experts, i.e., from the respective component manufacturers and vendors.

Today's PLM systems allow formation of cross-functional design teams along with involvement of suppliers and vendors, early in the design process. They provide the ability to query and retrieve data from third party databases (e.g., databases of applicable regulations, material composition databases), as well as secure access

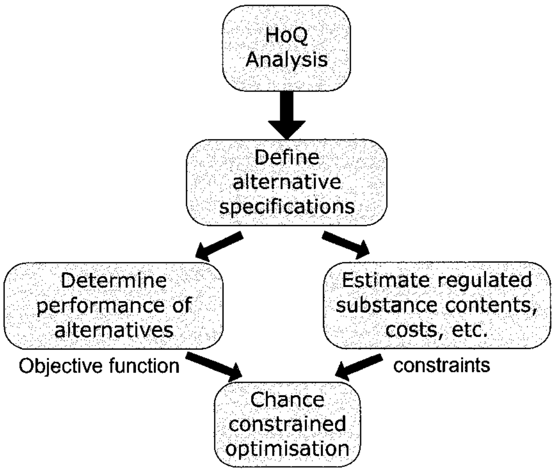


Figure 2.1: Steps for selecting substance content specifications for components

functionality to enable feedback from the suppliers in these early design stages. In this section, we present a framework that utilizes the functionalities provided by PLM for selection of material and processing specifications (with the corresponding substance content specifications) for components. The framework combines consideration of regulatory requirements, which are quantitative but indeterministic in the early design stages, with a rankings-based approach similar to that used by Vairaktarakis [14] and Kuppuraju [16]. We assume that a design configuration has already been chosen in the conceptual design phase, and the specifications need to be decided for the components in this configuration. Figure 2.1 shows the steps involved in the framework. These steps are explained below:

1. *HoQ analysis to decide relative importance of components:* In the first step, the design team uses a House of Quality (HoQ) analysis to determine the contribution of individual components to the performance of the product as a whole. The goal of this step is to quantify the relative importance of components based

upon the functional requirements of the product. This is required in order to determine the product performance for any combination of alternatives that may be selected. We recognize that the HoQ approach is more suited for products with a modular architecture, and becomes complicated for more integral architectures with complicated, overlapping function chains. Other methods, such as, utility analysis [23], pairwise comparison [24], Pugh Matrices [25], etc., can also be suitably used for this purpose depending upon the nature of the product. This step also establishes the criteria (such as, strength, corrosion resistance, thermal conductivity, etc.) for evaluating the performance of the alternatives defined for each component.

2. *Define alternative material and processing specifications for each component:* The next step for the designers is to completely define the component alternatives (i.e., alternative sets of specifications for each component). For standard parts, this can be done by merely stating the catalog numbers of the parts. However, for custom-built parts, defining the alternatives involves stating the materials to be used, manufacturing and processing steps required, in addition to the limits on regulated substances. For example, one component alternative may be defined as - {material = C60 steel, Pb content $\leq 0.2\%$ by weight, case hardened, Cr content $\leq$ 10mg}.

3. *Determine performance rating of each alternative:* Once alternative specifications have been defined, each alternative is rated on a fixed cardinal scale, with respect to how well it is expected to meet the requirements of the component.

This "performance rating" is arrived at by combining the expected performance of the alternative under the different performance criteria for the component, as determined in step 1. To estimate the performance of an alternative in each criterion, previously used parts made to same or similar specifications, or a preliminary analysis based upon computer models or prototypes, may be required. In addition, the performance in each criterion is normalized with respect to the ideal performance to make it independent of any system of measurement.

4. *Collect information related to regulatory and budgetary requirements:* Concurrently with step 3, a query-retrieval system is used to gather estimates from suppliers and 3-party databases, about amounts of hazardous substances, and recyclable material expected in the different alternatives. It should be noted that detailed design of each alternative is not carried out at this stage, and hence the exact dimensions, weight, or surface area, etc., of the alternatives are not known. Consequently, the amounts of specific substances (e.g., lead in alloy, or chromium in surface plating, etc.) are not deterministically known. Estimates of the production costs are also collected at this stage.

5. *Solve optimization problem to identify best combination of alternatives:* Finally, a stochastic optimization problem is set up, with binary decision variables to indicate whether or not a particular alternative is chosen for a component. Constraint equations are created corresponding to regulatory and budgetary requirements using the the information collected for each component alternative. The overall product performance forms the objective function, which is

maximized. The solution of this problem yields the best combination of specifications for the components of the product.

Following the steps outlined above, designers can effectively account for end-of-life regulations in the embodiment stage of product design. Step 1 involves quantification of qualitative information, such as relative importance of strength and corrosion resistance in a component's performance, and relative importance of individual components in the overall product performance, etc. Standalone software tools, using HoQ analysis or pairwise comparison methods, are available for such quantification, and can be readily integrated with an existing PLM system. Definition of alternative specification sets, in Step 2, requires knowledge of available technologies for making each component. This would require the design team to share expectations about the functional properties with the suppliers or domain experts, and seek feedback with regards to the availability and suitability of alternative technologies. A standardized representation to describe the alternative specifications within the PLM system may be required to automate generation of queries and collection of estimates in the subsequent steps. However, development of such a standard is outside the scope of this research. Steps 3 and 4 require the design team to obtain quantitative estimates of cost, performance, hazardous substance content, etc., from the suppliers of each component. Systems for issuing requests-for-quotes are already used to gather information about component costs, and similar systems will be required to gather other information about the component alternatives. Moreover, recognizing the inherent uncertainty in determining these quantities at such an early design stage, the systems can be modified allow suppliers to provide estimates in terms of ranges or probability distributions.

Thereafter, the main challenge is to use such probabilistic information and still be able to make the optimal choice of specifications for each component in the product. For this purpose, we propose the use of stochastic optimization, and specifically "chance constrained programming". The following sections describe the formulation of the chance constrained programming problem, and present an approach to solve the resulting formulation.

2.5 Chance constrained programming formulation

As described in the previous section, the proposed framework for selection of regulated substance specifications for components requires solution of a chance constrained optimization problem. In this section, we explain the mathematical formulation of the chance constrained programming problem.

For the purpose of this research, we assume that only a finite number of discrete alternatives have been defined for each component. As discussed in the previous section, the relative importance of components in the configuration, the performance ratings of individual component alternatives, as well as estimates of production cost and regulated substance contents for each component alternative, have been obtained prior to setting up the optimization problem.

Let;

n: number of components in the chosen product configuration

p_k: k^{th} component of the product ($k \in 1, ..., n$)

m_k: number of alternative choices/specifications for component p_k

p_{kl}: l^{th} alternative choice for component p_k $(l \in 1, ..., m_k)$

c_{kl}: cost of p_{kl}

$\Re_{kl}$: performance rating of component p_{kl}

w_k: relative importance of component p_k to product performance

We create binary decision variables denoting whether or not a particular component alternative is to be selected

$$x_{kl} = \begin{cases} 1 & \text{iff } p_{kl} \text{ is selected for } p_k \\ 0 & \text{otherwise} \end{cases}$$

The following constraints on the decision variables are necessary to ensure that they can take only values 1 or 0, and that only one alternative can be selected for any component

$$x_{kl} \in \{0, 1\} \tag{2.1}$$

$$\sum_{l=1}^{m_k} x_{kl} = 1 \tag{2.2}$$

The objective of the optimization is to maximize the product's performance. The summation $\sum_{l=1}^{m_k} \Re_{kl} x_{kl}$ gives the performance rating of the selected alternative of component p_k. Consequently, the portion of the product's performance dependent on performance of component p_k is given by $\sum_{l=1}^{m_k} w_k \Re_{kl} x_{kl}$. And the total product performance, after accounting for all components, is given by equation (2.3), which forms the objective function to be maximized.

$$\max \sum_{k=1}^{n} \sum_{l=1}^{m_k} w_k \Re_{kl} x_{kl} \tag{2.3}$$

It should be noted that while formulating the objective function, the overall product performance is calculated as a linear sum of the performances of individual components, weighted by their relative importances. We recognize that such a compensatory function to calculate overall product performance is not universally applicable. In most products, the product performance is a complex function of individual component performances, that also includes non-linear and non-compensating behavior of performance attributes. Nevertheless, in this research we approximate the performance objective as a linear function of individual component performances. We envisage that the algorithms presented in this research can be extended to accommodate more stringent measures of product performance, as discussed in section 2.7.

Finally, constraints are added to the above formulation to account for substance regulations, production cost requirements, etc. The applicable regulatory limits and the corresponding constraint equations will vary depending upon the product category, country where the product is marketed, and the nature of the components (i.e., parts containing lead/mercury as an alloying element, parts containing hazardous substances in surface coatings, plastics containing fire retardants, etc.) involved in the product. Examples of formulation of constraint equations for specific regulatory requirements are provided in Appendix A. In order to indicate the types of constraints that will be encountered in this formulation, we classify the constraints into the following categories:

- *Constraints applicable to a subset of parts:* Certain regulations apply directly to a specific component or a group of components in the product. For example, under the End of Life Vehicles (ELV) directive [4], the amount of hexavalent chromium (CrVI) contained in chromium plated parts is regulated separately from other parts containing CrVI. Mercury (Hg) content in florescent lamps, lead (Pb) contained as an alloying element in steel parts, and Pb contained in electronic ceramic parts, are other examples. The resultant constraint equations will take the form of equation (2.4), where H represents the property (such as, Pb content or Hg content) being regulated in a subset (A) of components and H_{limit} is the regulatory limit applicable directly to the component. Depending upon the expressiveness of the representation scheme used to define component alternatives, the subset A may be determined automatically by the PLM system for each regulation, or may need to be defined manually by the design team. The regulatory limit (H_{limit}) may be an absolute value, or a function of some property of the component (such as weight). Correspondingly, H_{kl} stands for the value of the property in alternative p_{kl}.

$$\sum_{k \in A} \sum_{l=1}^{m_k} H_{kl} x_{kl} \leq H_{limit} \tag{2.4}$$

$$\ldots \text{ for some } A \subset \{1, 2, \ldots n\}$$

- *Product level constraints:* This category refers to regulations or constraints that apply to the product as a whole. Constraints arising from recyclability targets, or limits on total amount of volatile organic compounds (VOCs) in the product, will fall under this category. For example, in equation (2.5), I_{kl} denotes the amount of recycled material in component alternative p_{kl}, while I_{min} represents the target for recycled content in the product. Similarly, the budgetary constraint equation (2.6), where c_{kl} represents the production cost of component alternative p_{kl} and B represents the allocated budget, also falls under this category.

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k} I_{kl}x_{kl} \geq I_{min} \tag{2.5}$$

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k} c_{kl}x_{kl} \leq B \tag{2.6}$$

- *Part compatibility constraints:* Constraints of the form of equation (2.7) arise if an alternative for one component is incompatible with an alternative for another component. For example, a steel bolt cannot be specified in combination with a nylon nut, although using a nylon nut may increase recyclability. Such incompatibilities usually arise between mating components. We shall refer to them as *part compatibility constraints.* Other reasons for incompatible mating parts can be possibility of local corrosion due to material combination at contact, unequal thermal expansion coefficients, unequal hardness causing excessive wear on one part, etc.

$$x_{ag} + x_{bh} = 1 \tag{2.7}$$

... for some mating components $a, b \in \{1, 2, ...n\}$,

and component alternatives $g \in \{1, 2, ...m_a\}$, $h \in \{1, 2, ...m_b\}$

As discussed in the previous section, properties such as Pb content (G_{kl}), CrVI content (H_{kl}), or cost of production (c_{kl}), for each component alternative (p_{kl}) are not deterministically known. Instead, they are available as estimates and hence are probabilistic quantities. Solving a deterministic optimization problem using mean values can lead to a solution with a high probability of being infeasible, while using worst case values may yield a solution that is far from optimal. Instead, the chance constrained programming model works directly with the estimated probability distributions of these quantities, and allows the user to specify the minimum probability (α_i) with which any solution must satisfy a particular constraint. Thus, in the chance constrained programming formulation, constraint equation (2.4) will be converted into the following chance constraint:

$$P\left(\sum_{k \in A} \sum_{l=1}^{m_k} H_{kl} x_{kl} \leq H_{limit}\right) \geq \alpha_i \tag{2.8}$$

Solving the optimization problem under such a chance constraint inherently involves a risk ($(1 - \alpha_i) \times 100\%$) that the solution obtained will be found to violate the original constraint (2.4). This risk is controlled by the user, which in our case is the design team, by choosing the value of α_i. The choice of α_i will depend upon a number of factors, such as confidence in property estimates, flexibility of design to make changes, lead time available for changes, penalties for non-compliance with the specific constraint, financial risk bearing capacity of OEM, etc. For example, if the OEM wants more innovative designs and has sufficient time to make modifications to correct any constraint violation, then a lower value of α_i (implying higher risk) will be chosen. However, if the OEM wants to be conservative and ensure that a compliant product will be obtained, a higher value of α_i will be chosen. We envisage that using knowledge and experience generated during development of products over time, designers will be able to determine acceptable values of α_i depending upon the product domains and the types of constraints.

A chance constraint in the form shown in equation 2.8 above, where a probability is assigned for a single constraint being satisfied, is referred to as "individual" or "separate chance constraint". Often times it is more intuitive for the user to specify a probability for a set of constraints to be satisfied together. For example, the user may want to specify the probability of satisfying Asian market requirements, or the probability of satisfying all requirements of the ELV directive. Such cases are referred to as "joint chance constraints" and will be of the form shown in equation (2.9) below.

$$P\left(\sum_{k\in A}\sum_{l=1}^{m_k} H_{kl}x_{kl} \leq H_{limit}; \ldots; \sum_{k=1}^{n}\sum_{l=1}^{m_k} I_{kl}x_{kl} \geq I_{min}\right) \geq \alpha_j \qquad (2.9)$$

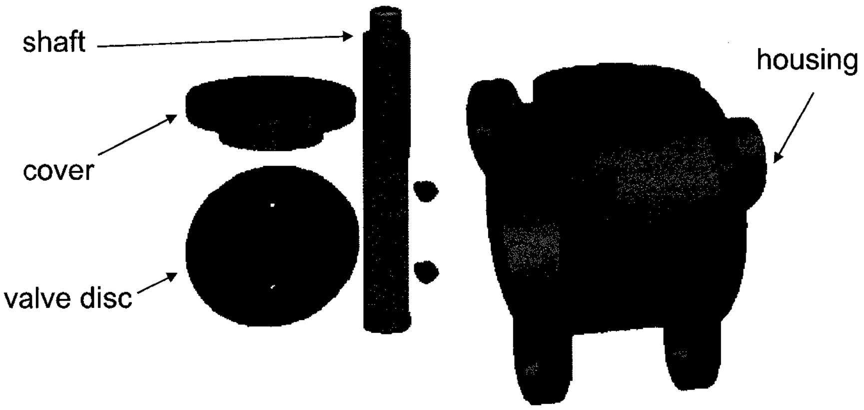


Figure 2.2: Butterfly valve configuration

2.6 Solution Methodology

As described in the previous section, selecting the optimal set of specifications involves solving a binary chance constrained optimization problem, wherein the right hand sides of the constraints are constants, while the coefficients of the decision variables are random distributions.

In this section, we shall demonstrate the algorithm to solve the chance constrained formulation with the help of a simple example. Let us consider that a design team has to design an industrial flow control valve for carrying a corrosive liquid. After comparing different options in the conceptual design phase, the team chooses a butterfly valve configuration, as shown in Figure 2.2. For simplicity, let us consider that the only applicable regulation is a limit on amount the CrVI, which is contained in chromium platings. For the category of valves under consideration, this limit is stated as an absolute value of $30mg$ of CrVI per valve. Additionally, the designers need to ensure that the production cost of the valve does not exceed \$300.

As shown in Figure 2.2, the valve configuration has four components, for which

Table 2.1: Performance criteria and relative importances of each component

k	**Component** (p_k)	**Performance Criteria**	**Relative Importance** (w_k)
1	housing	castability case hardenability machinability corrosion resistance	5
2	cover	machinability hardenability	2
3	valve disc	machinability corrosion resistance	3
4	shaft	machinability hardenability corrosion resistance	3

CrVI limit specifications have to be determined (the two screws are assumed to be standard inventory parts that do not contain CrVI). The relative importance (w_k) of each component, and the properties used for measuring the performance of the components, are shown in Table 2.1. Also for simplicity, let us assume that each component can be manufactured in only two ways; namely, without any chromium plating, or with chromium plating on the entire exposed surface area. Thus, the CrVI content specifications can be made by specifying whether the component should have chromium plating or not, i.e., there are two alternative specifications for each component. Since the detailed design of the components has not been completed, the exposed surface area of the components is not known, and the amounts of CrVI in chromium plated alternatives are estimated as normal probability distributions (represented by the mean and standard deviation). Similarly, estimates of production costs for the alternatives are also available as normal distributions. This information is tabulated in Table 2.2 on the following page.

Table 2.2: Information about component alternatives

p_k	p_{kl}	**alternative**	**CrVI content** (H_{kl})(mg)		**Cost** (c_{kl})($)		**Perf. Rating** ($\Re_{kl}$)
			$\bar{H}_{kl}$	$\sigma_{H_{kl}}$	$\bar{c}_{kl}$	$\sigma_{c_{kl}}$	
housing	p_{11}	ductile iron	0	0	95	2	5
	p_{12}	ductile iron with Cr plating	19	2.1	145	2	7
cover	p_{21}	medium carbon steel	0	0	45	2	5
	p_{22}	medium carbon steel with Cr plating	2.2	0.3	65	2	7
valve disc	p_{31}	ductile iron	0	0	35	2	5
	p_{32}	ductile iron with Cr plating	8	0.8	55	2	7
shaft	p_{41}	medium carbon steel	0	0	45	2	5
	p_{42}	medium carbon steel with Cr plating	6	1	65	2	6

We shall consider two separate cases for the two categories of chance constraints that can arise depending upon the way the design team chooses or assigns the acceptable risk of the constraints being violated.

2.6.1 Case 1: Individual Chance Constraints

For the first case, let us assume that the design team is willing to accept a 10% risk on each of the constraints (i.e., for each constraint, there is a 10% chance that the solution, upon detail design, may end up violating the constraint). This means that the solution must have 90% probability of satisfying each constraint individually. Thus, probabilistic constraints will be expressed as:

$$P\left(\sum_{k=1}^{n}\sum_{l=1}^{m_k} c_{kl}x_{kl} \leq 300\right) \geq 0.9 \tag{2.10}$$

$$P\left(\sum_{k=1}^{n}\sum_{l=1}^{m_k} H_{kl}x_{kl} \leq 30\right) \geq 0.9 \tag{2.11}$$

As explained in section 2.5, the above constraints are called "individual chance constraints" (ICC). Since the random variable coefficients in these equations are given as normal probability distributions, we can convert these individual chance constraints into equivalent deterministic constraints by integrating over the resultant probability distribution function. It should be noted, however, that deriving the deterministic equivalent is generally difficult due to complicated multivariate integration and is only practical if the random variables involved follow certain distributions, namely normal, uniform, exponential and lognormal distributions [26].

We shall now explain the conversion of the chance constraint, equation (2.10), into a linear deterministic constraint. The random variables in equation (2.10) are normally distributed. The summation $\sum_{k=1}^{n}\sum_{l=1}^{m_k} c_{kl}x_{kl}$ is a sum of normal distributions and, therefore, itself a normal distribution, with mean $\mu_{cost} = \sum_{k=1}^{n}\sum_{l=1}^{m_k} \bar{c}_{kl}x_{kl}$ and standard deviation $\sigma_{cost} = \sqrt{\sum_{k=1}^{n}\sum_{l=1}^{m_k} {\sigma_{c_{kl}}}^2 {x_{kl}}^2}$. For any normally distributed random variable $B(\mu, \sigma)$ and constant K, the probability that $B \leq K$ is given by the relation;

$$P\left(B \leq K\right) = \frac{1}{2}\left(1 + erf\left(\frac{K-\mu}{\sigma\sqrt{2}}\right)\right)$$

Using this relation we can convert the chance constraint equation (2.10) into the deterministic equation:

$$\frac{1}{2}\left(1 + erf\left(\frac{300-\mu_{cost}}{\sigma_{cost}\sqrt{2}}\right)\right) \geq 0.9 \tag{2.12}$$

... where μ_{cost} and σ_{cost} are functions of x_{kl}

Segara, et al. [27] have demonstrated that the above non-linear deterministic constraint can be further linearized using a simple approximation. To show this, we shall first re-write the non-linear constraint equation (2.12) as follows:

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k} \bar{c}_{kl}x_{kl} + Z\sqrt{\sum_{k=1}^{n}\sum_{l=1}^{m_k} {\sigma_{c_{kl}}}^2 {x_{kl}}^2} \leq 300 \tag{2.13}$$

$$\sum_{k=1}\sum_{l=1} \bar{c}_{kl}x_{kl} + Z\sqrt{\sum_{k=1}\sum_{l=1} {\sigma_{c_{kl}}}^2 {x_{kl}}^2} \leq 300$$

... where Z is obtained from the standard normal distribution $N(0,1)$

($Z = 1.2817$ for 90% probability)

The non-linear equation (2.13) can then be approximated by the linear constraint equation (2.14) below:

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k}\bar{c_{kl}}x_{kl} + Z\sum_{k=1}^{n}\sum_{l=1}^{m_k}\sigma_{c_{kl}}x_{kl} \leq 300 \tag{2.14}$$

This is a conservative approximation, since the value $\sum_{k=1}^{n}\sum_{l=1}^{m_k}\sigma_{c_{kl}}x_{kl}$ is greater than the value $\sqrt{\sum_{k=1}^{n}\sum_{l=1}^{m_k}{\sigma_{c_{kl}}}^2{x_{kl}}^2}$.

Similarly, the CrVI content constraint is also converted into a deterministic constraint. When all the individual chance constraints are converted into linear deterministic constraints the chance constrained optimization problem is transformed into a binary (0-1) integer linear programming problem. Usual integer linear programming techniques, such as branch-and-bound or cutting plane methods, can be used to efficiently solve the problem. For the present example, MATLAB's binary integer linear programming routine, which uses a branch and bound technique, was used to arrive at the solution. The resulting solution is shown in Table 2.3 on the next page. The solution that would have been obtained using worst case estimates (i.e., using 99.8% confidence values for estimates) is also presented for comparison.

2.6.2 Case 2: Joint Chance Constraints

Now, let us consider the case where the design team desires 90% confidence that the solution obtained, upon detailed design, will satisfy all the constraints involved. That means, that the solution must satisfy both the cost and the CrVI content constraints jointly with a probability of 90%. This is expressed mathematically as shown in equation 2.15:

Table 2.3: Results for case study - ICC case

	Chance constrained model	**Optimization using worst case estimates**
housing	plated	plated
cover	not plated	not plated
valve disc	plated	not plated
shaft	not plated	not plated
CrVI content (mg)	**mean = 27** $P\,(CrVI \leq 30) = 0.909$ $P\,(CrVI \leq 29.88) = 0.9$	**25.54**
Cost (\$)	**mean = 290** $P\,(Cost \leq 300) = 0.99$ $P\,(Cost \leq 295.16) = 0.9$	**290**
Performance rating	**81**	**75**

$$P\left(\sum_{k=1}^{n}\sum_{l=1}^{m_k} c_{kl}x_{kl} \leq 300; \sum_{k=1}^{n}\sum_{l=1}^{m_k} H_{kl}x_{kl} \leq 30\right) \geq 0.9 \tag{2.15}$$

Transformation of joint chance constraints (JCC) optimization problems into deterministic problems leads to complicated non-linear constraints, which often lead to a non-convex solution space, although the individual constraint equations are linear and convex. Methods using Monte Carlo simulations or creation polyhederal outer approximations of the solution space have been previously used for medium scale joint chance constrained problems with continuous variables. Other implementations involving discrete approximations of the constraint equations have also been used for problems with large number of constraints [18].

Instead, we use an algorithm to approximately solve the JCC problem by systematically solving a set of more conservative ICC problems that collectively approximate the feasible space for the original JCC problem. In order to do that, we assume that the estimated random variable coefficients, and consequently the constraint equations, are independent of each other. The consideration of correlated random variable coefficients is beyond the scope of this research. Using this assumption, we can introduce two new parameters (ϕ_1 and ϕ_2) to replace the joint chance constraint equation (2.15) by the following set of constraints:

$$P\left(\sum_{k=1}^{n}\sum_{l=1}^{m_k} c_{kl}x_{kl} \leq 300\right) \geq \phi_1 \tag{2.16}$$

$$P\left(\sum_{k=1}^{n}\sum_{l=1}^{m_k} H_{kl}x_{kl} \leq 30\right) \geq \phi_2 \tag{2.17}$$

$$\phi_1\phi_2 = 0.9 \tag{2.18}$$

$$\ldots\ 0 \leq \phi_1, \phi_2 \leq 1$$

As shown in section 2.6.1, equations (2.16) and (2.17) can be transformed into linear deterministic constraints. However, equation (2.18) remains as a non-linear, non-convex constraint.

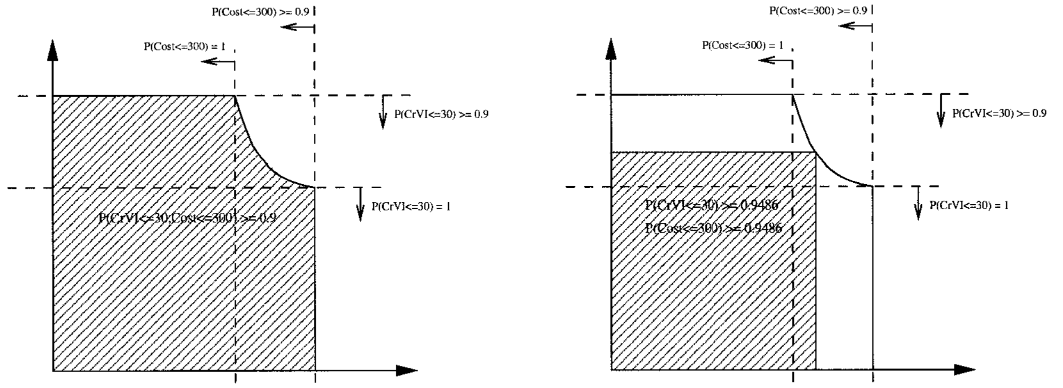
Thus, for any joint chance constraint involving N individual constraint equations, we introduce N parameters ($\phi_i : i \in \{1, \ldots, N\}$) to get N individual chance constraints. We then approximate the JCC problem by an ICC problem, by choosing values for ϕ_i, such that $\prod_{i=1}^{N} \phi_i$ is equal to the required probability of jointly satisfying the constraints. Thus, the parameters ϕ_i decide the manner in which the acceptable risk of failure of the joint constraint is divided amongst individual constraints. The resulting ICC problem is a conservative approximation of the JCC problem. In order to get a better approximation of the feasible space, we systematically generate a number of ICC approximations in the following manner:-

For the first ICC approximation, the designer specified risk is shared equally among all N individual constraints. The next set of ICC approximations are generated by equally sharing the risk among combinations of $(N-1)$ individual constraints with the remaining constraint being satisfied at all times. Subsequent ICC approximations are generated by sharing the risk among combinations of $(N-2)$ constraints, $(N-3)$ constraints, and so on. In this way, $(2^N - 1)$ ICC problems are solved to find a solution to the original JCC problem.

We shall explain this process for the valve design example. Consider that all combinations of alternatives are represented as discrete points on a plane, where the X-axis measures the probability of the combination meeting the cost constraint, while the Y-axis measures the probability of the combination meeting the CrVI content constraint. Accordingly, Figure 2.3(a) on the following page shows the feasible solution space for the joint chance constraints case, as defined by equations (2.16), (2.17), and (2.18). Instead of searching for the optimal solution in this non-convex, non-polyhederal space, we solve a set of conservative ICC approximations.

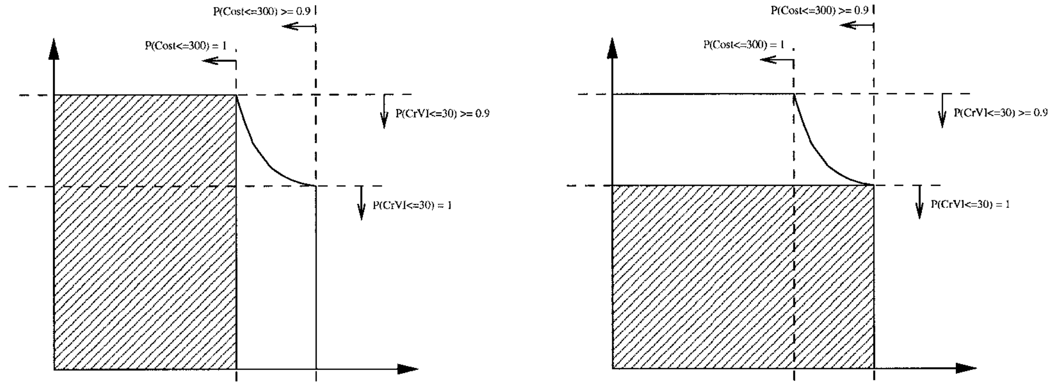
For the first ICC approximation, we divide the acceptable risk of failure of the joint constraint equally among the two individual constraint equations (2.16) and (2.17), and accordingly set $\phi_1 = \phi_2 = \sqrt{0.9} = 0.9486$. Consequently, the non-linear constraint equation (2.18) can be discarded. The solution space searched by this ICC problem is shown in Figure 2.3(b).

Subsequently, we solve two more ICC approximations by allowing the entire ac-



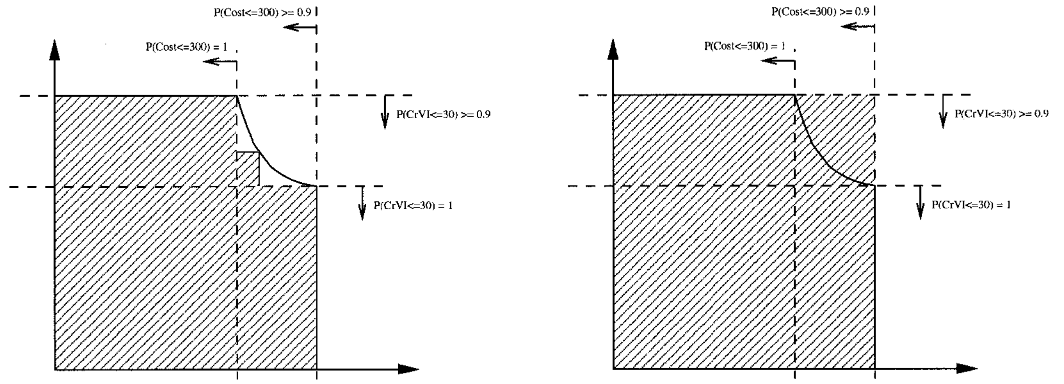
(a) Feasible space for original JCC problem

(b) Search space for ICC approx. $\phi_1 = \phi_2 = 0.9486$



(c) Search space for ICC approx. $\phi_1 = 0.9986; \phi_2 = 0.9012$

(d) Search space for ICC approx. $\phi_1 = 0.9012; \phi_2 = 0.9986$



(e) Effective space searched by ICC approximations

(f) Search space to find upper bound on objective function value $\phi_1 = 0.9; \phi_2 = 0.9$

Figure 2.3: ICC approximations to JCC problem

ceptable risk to be taken up completely by one of the individual constraint at a time. The solution spaces searched are shown in Figures 2.3(c) and 2.3(d). It should be noted that since the random variables in our case are normally distributed, it is not possible for any solution to meet a constraint with 100% probability. Therefore, we consider that the solution meets the constraint at all times if it meets it with 99.86% probability (which corresponds to the commonly accepted 3σ limit). Consequently, in order to stay within the specified acceptable risk, the remaining constraint has to be satisfied with 90.12% probability. The total solution space searched by all three ICC approximations together is shown in Figure 2.3(e). The optimal solutions obtained for the three ICC approximations is shown in Table 2.4 below. Accordingly, the solution where chromium plating is specified on the housing and the cover and has a performance rating of 79 is selected as the solution for the JCC problem.

Table 2.4: Results for case study - JCC case

	ICC approx. #1 $\phi_1 = \phi_2 = 0.9486$	ICC approx. #2 $\phi_1 = 0.9986; \phi_2 = 0.9012$	ICC approx. #3 $\phi_1 = 0.9012; \phi_2 = 0.9986$	ICC approx. for upper bound $\phi_1 = \phi_2 = 0.9$
housing	not plated	not plated	plated	plated
cover	plated	plated	plated	not plated
valve disc	plated	plated	not plated	plated
shaft	plated	not plated	not plated	not plated
CrVI content (*mg*)	**mean = 16.2**	**mean = 10.2**	**mean = 21.2**	**mean = 27**
Cost ($)	**mean = 280**	**mean = 260**	**mean = 290**	**mean = 290**
Performance rating	**78**	**75**	**79**	**81**

The last column in Table 2.4, shows the solution obtained for an ICC problem in which each of the individual constraints have to be satisfied with the same probability specified for the joint chance constraint. Clearly, this problem includes solutions that violate the JCC problem. However, as shown in Figure 2.3(f), the feasible space for the JCC problem is a subset of the feasible space of this problem. Consequently, the solution to this problem provides an upper bound on the performance rating of the solution to the JCC problem. In JCC problems involving a large number of constraints, this upper bound can be effectively used to terminate the successive solution of ICC approximations if a solution with performance rating sufficiently close or equal to the upper bound is obtained.

2.7 Limitations and Future Work

In this chapter, we have proposed a new approach for OEMs to account for regulatory requirements early in the design of new products, with the aim of reducing downstream costs of compliance. In its current form, the framework presented has certain limitations. The number of assessments required in the House of Quality analysis increases rapidly as the number of components in the product and the number of performance criteria increase. When these assessments, as well as assessments of component performance, are carried out by multiple evaluators, procedures to adjust for differences in application of rating scales will be required. Thurston [23] provides a discussion of limitations of the utility assessment procedures, and bias due to preferences of team members, when using utility analysis for design tradeoff problems. Advances reported in literature toward overcoming these limitations, will need to be studied in future to improve the scalability and consistency of the evaluation steps.

Sensitivity of QFD approaches has previously been studied in literature [28, 29]. The methods are found to be robust against changes in the rating scales used, or changes in weights assigned to customer requirements. Although we have not explicitly studied the sensitivity of our method, we expect it to show similar robustness to variations in assessments of individual component importance, variations in performance estimates for alternatives, as well as variations in weights used for various performance criteria to decide the performance ratings. An important topic of future research should consider the stability and sensitivity of the results to the probability distributions used to estimate properties of alternatives for which there is incomplete information. Theoretically, owing to the presence of discrete solutions (i.e., the combinations of alternative specifications for components) a small change in the estimated probability distributions may lead to a different choice of optimal solution with a significant change in the corresponding objective function value. However, to ascertain the sensitivity in practical design situations a statistical study of alternatives generated during design will be required. Dupačová [30] describes the ways and means of statistical sensitivity analysis for stochastic programs based on Gâteaux derivatives. Similar methods can be used to establish the sensitivity of our method for different categories of products.

In this research, we approximate the overall product performance using a weighted sum of individual component performances. In order to account for non-linear and non-compensating behavior of certain performance attributes, the use of separate functions to aggregate component performances in each criterion need to be studied.

Subsequently, a multi-objective optimization problem can be formulated considering all attributes that contribute to the product's performance.

As mentioned in section 2.6.2, the method for solving the joint chance constrained problems requires that the random variable coefficients are mutually independent. However, covariance between different uncertain parameters is often observed in practical cases. The relation between the parameters can be defined using covariance matrices or conditional probability distributions. The effects of this covariance on the solution methodology presents an interesting avenue for future research. Another potential direction for extending this research is the use of continuous decision variables to represent choice of certain specifications, thus formulating the problem as a mixed continuous-integer variable problem.

Addressing these issues will extend the scope of this work enabling the framework to be used for practical cases by any original equipment manufacturer.

CHAPTER III

Decision support system for evaluation of impacts of an Engineering Change

Intelligent selection of regulated substance content specifications, as discussed in Chapter II, cannot ensure that design changes will not be required at a later stage. It has been observed that late design changes are costly and often cause delays in production due to unanticipated effects on other parts and processes. Therefore, comprehensive evaluation of proposed changes is required. At present, this process relies heavily on the knowledge and experience of the people handling these changes. This chapter presents a method to use a predefined knowledge-base and dynamic workflow generation to enable systematic evaluation of proposed Engineering Changes (ECs). We further describe a method to use experience from past ECs to facilitate the evaluation process.

3.1 Motivation

Often times regulatory violations or high production costs to meet the regulations can be avoided by making suitable changes to the design, materials, or processing of components, or by modifying the product configuration. Changes may also be required to adjust the product for revised regulations, availability of newer technology, or changes in available end-of-life treatment facilities. However, such changes may have cascading effects on other parts and processes of the product. These effects must be carefully studied and evaluated before implementing the change. In most companies, such changes are handled under a systematic Engineering Change Management (ECM) framework. However, evaluation and approval of engineering changes (ECs) is an expensive and time consuming process requiring considerable experience and expertise on the part of the users. A 1988 survey of US and European companies [31] found that the average administrative costs encountered were of the order of $1400 per change. A similar survey of companies in Hong Kong [32], carried out in 1999, found that there were between 5 to 60 active ECs in a company at any given time. The processing time for an EC was found to vary between 2 to 36 person-days.

ECs related to regulatory requirements need to be resolved quickly to avoid loss of production or possibility of heavy fines. However, hasty approval of changes without evaluation can cause a number of unanticipated problems due to part or process incompatibility, wastage of inventory parts, unavailability of new raw materials required, etc. Thus, there is a need to enhance the EC evaluation process to enable companies to carry out detailed evaluation in a manner that is quick, systematic and less dependent on the experience or expertise of the end user.

3.2 Objective

The goal of this research phase is to develop a decision support system that can facilitate systematic evaluation of the engineering and business impacts of a proposed Engineering Change. The system should make use of available industry specific knowledge, and also capture and reuse knowledge generated in evaluation of past ECs, to assist the user during the evaluation process.

3.3 Literature Review

Although ECM is an important activity for the industry, it has not received adequate attention in academic research literature. Most of the early publications have either been surveys of industry practices, or efforts to reduce the impacts of ECs on manufacturing and inventory by adopting systematic document control systems [33]. Dale [34] published one of the first works directly addressing the ECM problem. He provides a detailed description of a change management system used in a multinational engineering company. He further mentions responsibilities of various departments and the EC coordinator, as well as qualities required in the ECM system for effective change management.

Krishnamurthy and Law [35] present a hierarchical method to store design descriptions. The original design is considered as the "root" and changes are added as branches to create a tree like structure with leaves describing the latest entities. Peng and Trappey [36] present a STEP (ISO 10303) schema for recording EC documents.

Huang and Mak [37] emphasize the need for a computer based ECC (Engineering Change Control) system to overcome the delays in paper based systems. They presented a survey of the use of computerized ECC tools in a set of UK companies. The survey found that the types of computerized tools used can be classified into three categories:

- word processors and spreadsheets to record changes along with basic CAD tools,
- dedicated ECC systems with custom forms and databases to store EC data and maintain change history, and
- PLM/PDM systems with full fledged configuration management, that can consider workflows, work-center configuration, BOM, along with CAD information.

While most previous efforts concentrated on managerial or document control aspect of engineering changes, a few methods have been developed to help the engineers predict the effects of an EC. Jarratt [38] reports the development of a prototype support tool to calculate the "risk" of change propagation, using statistical simulation. While the method quantifies the risk, it does not identify the actual downstream effects of the change. Rouibah and Caskey [39] propose a concurrent engineering style approach to evaluate an EC in a collaborative, multi-company environment. The method expresses each engineering decision as a value given to a "parameter". "Parameters" dependent on each other are "coupled" during creation and these "coupling relationships" can be used to propagate the effects of an EC. However, this method requires elaborate and consistent definition of parameters and coupling relationships every time any engineering decision is made. Moreover, it is unrealistic to expect that all information about a product or system can be captured as parameters.

This research adopts a new approach using dynamic workflows and past experience to evaluate proposed ECs. At this point, however, it is important to understand current ECM practices in industry. In the following section we shall briefly explain certain ECM terminology and practices, as well as the ECM tools provided by current, state-of-the-art PLM solutions.

3.3.1 ECM - Terminology and Practice

As indicated by Huang and Mak [37], ECM systems vary widely in terms of the processes followed as well as the sophistication of the tools used. Although different ECM procedures are followed in different companies, the underlying objectives are common. Any ECM system must:

1. strike a balance between comprehensive evaluation of the potential effects of an EC and the speed of the approval process, &
2. provide timely notification of the required changes to all concerned.

The generic steps involved in ECM can be divided into two phases, viz. prior to approval of the change and after approval, as shown in Table 3.1 on the following page. It is important to note that this research focuses on the steps prior to the approval of the change.

Most companies adopt systematic document based methods for controlling the EC process. The commonly used forms and documents include:

Table 3.1: Steps involved in ECM

Prior to EC approval	**After EC approval**
Initiate EC request describing change and reasons	Serve notification of change approval to all concerned
Collect information required for evaluation of engineering and business impact	Create new drawings, process plans, and maintaining history of changes
Submit proposal to managing committee	Raise new orders, process existing inventory, create workflow for implementation
Approve/reject/postpone proposal (with reasons)	Implement change according to planned schedule

- Engineering Change Request (ECR) forms - for initiating the change
- Problem Report (PR) forms - to report a problem in the product or process (treated in the same way as ECRs).
- Engineering Change Notifications (ECN) - to notify all concerned disciplines of an approved change, its effectivity dates, etc.
- Engineering Change Packages (ECP) - that include drawings, process plans, workflows, etc. required to implement the change
- Engineering Change Orders (ECO) or Work Authorization (WA) orders - to authorize implementation

Companies usually appoint an EC coordinator, who is responsible for collecting information required for evaluation of the requested change. The EC coordinator submits his findings to an Engineering Change Committee that decides whether or not to approve the change. Companies often distinguish between Full/Standard Track and

Fast Track approval procedures. Changes with low expected impact are handled through the Fast Track process, which employs a less elaborate approval mechanism. Typically, 80% of the ECs in a company follow the Fast Track process due to the prohibiting cost and time associated with the more robust and controlled Full Track process. Upon approval, the EC coordinator is also responsible for compiling the ECP, and monitoring the implementation of the change.

3.3.2 ECM in existing PLM solutions

ECM modules are an integral part of today's PLM/PDM systems. The modules usually conform to the requirements of the industry-standard Configuration Management II (CMII) closed-loop change model. The functionalities provided by these modules include:

- creation, editing and approval procedures for ECRs and WAs (ECOs)
- retrieval of assemblies, workflows and BOMs that include the object to be changed (provided such associations have been previously defined)
- notifying users of the changed parts or processes, implementation dates, etc.
- tracking and auditing the implementation of the change order
- verification of accuracy of the ECP and conformance to documented requirements
- maintenance of complete history of product changes executed during the product lifecycle

As can be seen in the above listing, typical ECM systems are mainly geared toward managing engineering change documentation. However, the core engineering analysis of the change is not directly addressed.

Most of the existing ECM modules use their workflow management capabilities for handling an ECR and directing the change process. A workflow specifies the order in which the change request will be sent to all concerned departments or individuals for approval, and the tasks to be completed before the request is forwarded to the next person. However, the entire workflow has to be predefined by the PLM system administrator (or the EC coordinator). An individual assigned a task may initiate a new workflow with tasks to study further impacts within his domain, through a process called "Change Elaboration". This may lead to confusion as individuals may not know the scope of their tasks, expecting others to evaluate aspects of the change that are not directly under their supervision. Moreover, they may not anticipate all the effects of the modifications they propose to accommodate the change request. PLM systems do provide some support to the users for predicting cascaded effects in the form of lists of assemblies, workflows, BOMs, etc. where the object being changed is used. However, this information is often insufficient to predict all potential effects of the requested change, which might be important with regards to product functionality, production delays or costs.

3.4 Dynamically generating the workflow for EC evaluation

As mentioned in the previous section, while PLM systems provide tools to manage EC documents and track the change process, the actual process for evaluating the effects of a proposed change has to be set up manually. This section describes our approach for comprehensive evaluation of a requested EC. The approach involves generation of the workflow for EC evaluation dynamically, with decision support based on predefined rules that capture industry specific knowledge. In section 3.5, we shall describe the use of knowledge generated from the evaluation of earlier ECRs to guide the users, and thereby improve the speed and effectiveness of the process.

The proposed method is based on an initial broad taxonomy of engineering changes that may be encountered in the company. This taxonomy is user defined and may vary in its size, scope, and level of detail, depending upon the type of company. For example, a small manufacturing unit may classify its engineering changes into:

- part geometry changes
- assembly configuration changes
- manufacturing process changes
- BOM changes
- and so on...

On the other hand, a large automobile manufacturing company may adopt a different classification, such as power-train part changes, chassis changes, workcenter configuration changes, etc.

We shall refer to each such defined category as a *change-type (CT)*. For each CT, a list of attributes (*set* A) is defined. In order to instantiate a change of a particular CT, all the attribute values must be defined. For example, while instantiating a

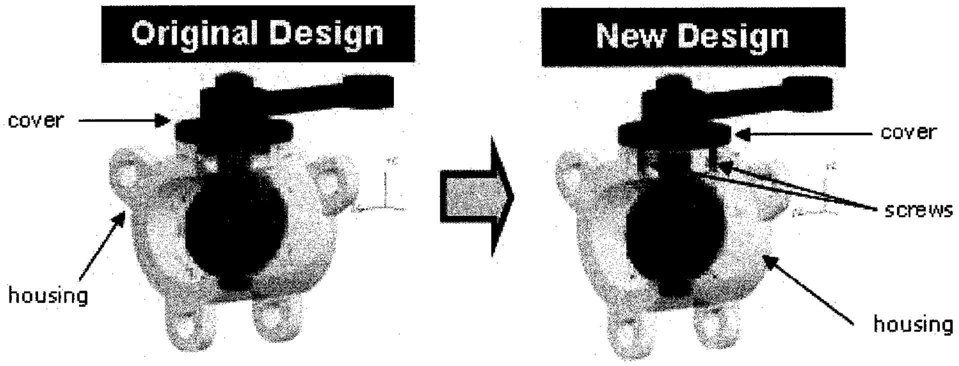


Figure 3.1: Example of a proposed engineering change

change with CT = *part geometry change* the user must enter the "part number" and "reason for change" attributes. Similarly for each CT, a list of all possible effects (*set* E) that might occur as a direct result of making that type of a change is also defined. Along with each effect $e \in E$, an individual or *agent* who can evaluate the effect is explicitly or implicitly defined. For example, the agent to evaluate an effect e = *effect on manufacturing process* may be defined as the supervisor of the machine shop where the changed part is manufactured. The actual individual, will be automatically determined using the information in the PLM system linking the part to the machine shop where it is made and subsequently to the shop supervisor. The agent may also be a software program which, for example, can calculate effect on product weight, or disassembly time, etc.

We shall explain the working of the system with the help of an example. Consider a butterfly valve as shown in Figure 3.1. Let us assume that there is a proposal to change the joint between the housing and the cover from a press fit to a screw connection. Accordingly, the requester initiates an ECR, filling in required information, such as a description of the proposed change, reasons for the change, name of

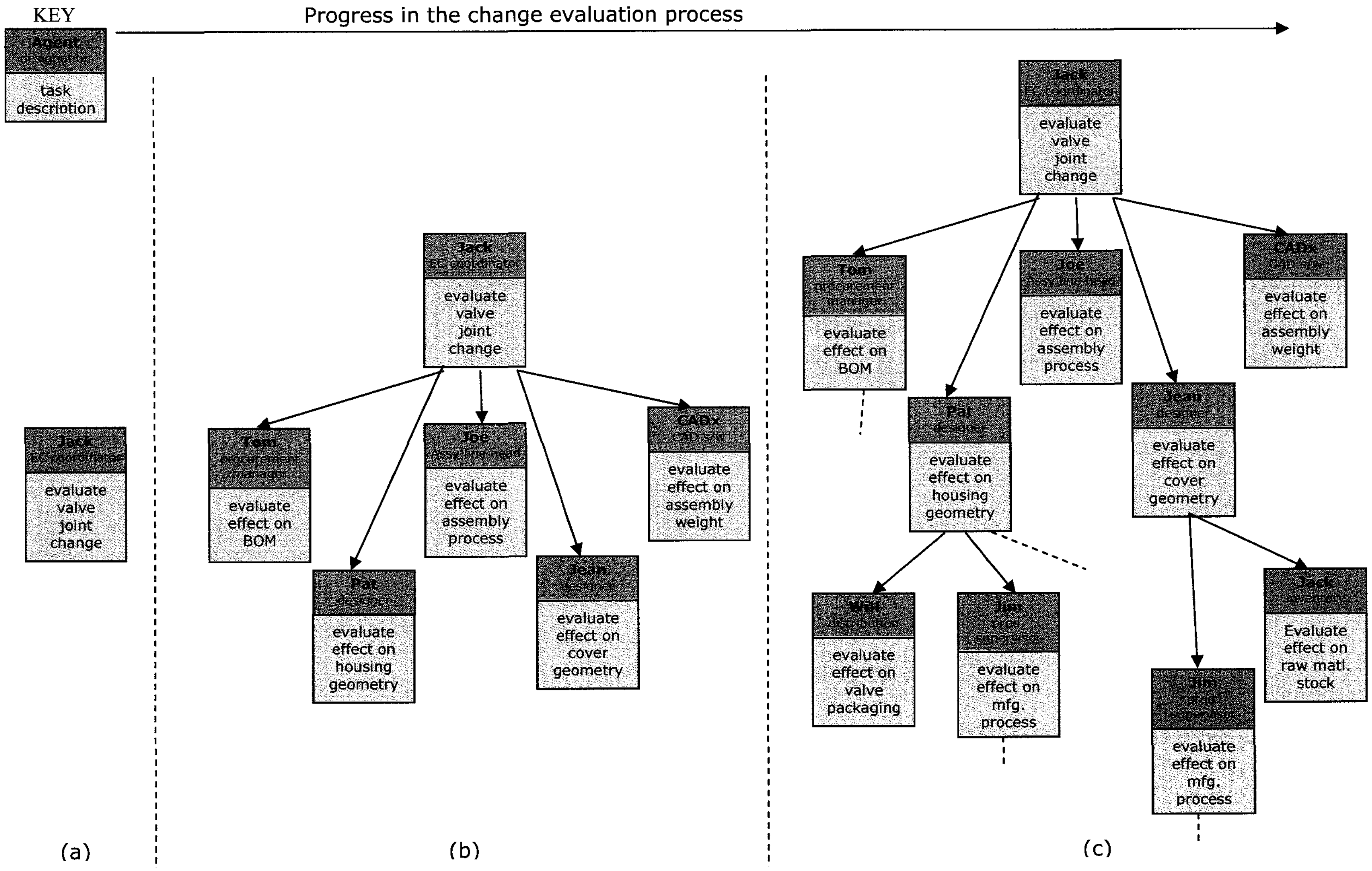
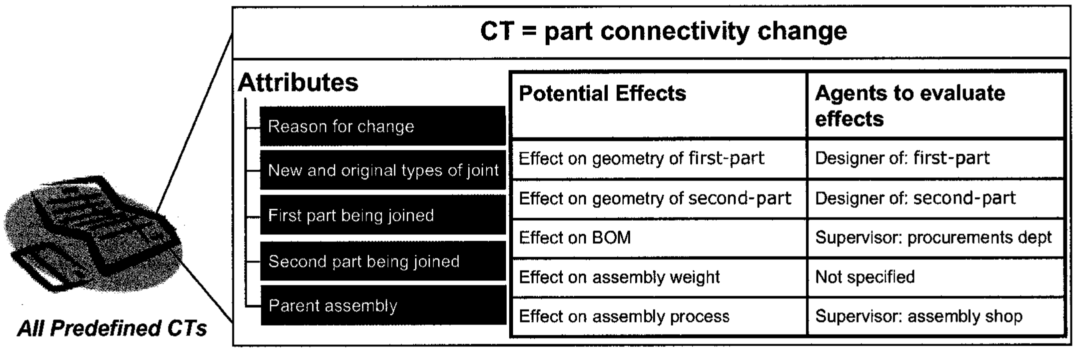


Figure 3.2: Dynamic generation of workflow for change evaluation (Butterfly valve example)



Potential Effects	Agents to evaluate effects
Effect on geometry of first-part	Designer of: first-part
Effect on geometry of second-part	Designer of: second-part
Effect on BOM	Supervisor: procurements dept
Effect on assembly weight	Not specified
Effect on assembly process	Supervisor: assembly shop

Figure 3.3: Attributes and effects for the *CT = part connectivity change*

requester, proposed effectivity dates, etc. This automatically initiates a workflow to study the effects of the proposed EC. The dynamic development of this workflow is shown in Figure 3.2 on the preceding page. Initially, as shown in Figure 3.2(a), only one task (or activity) is created in the workflow, which is to evaluate the change mentioned in ECR, and the task is assigned to a designated EC coordinator.

The EC coordinator then determines that the task being evaluated involves a change in the joint between two parts, which can be categorized under *CT = part connectivity change*. Based on the predefined list of attributes for *CT = part connectivity change*, the EC coordinator is prompted to enter values for the attributes, namely, part numbers of the individual parts being connected, original type of joint, proposed/new type of joint, and the reasons for proposing the change. Figure 3.3 shows predefined attributes (A) and possible effects (E) for the *CT = part connectivity change*. Note that the table in the figure is meant to serve as only an illustrative example and is not a comprehensive list.

Once the attributes have been entered, the system prompts the EC coordinator about the possible immediate effects of the change, as listed in E. The EC coordinator then creates new tasks in the change evaluation workflow corresponding to each effect $e \in E$ that needs to be studied, as shown in Figure 3.2(b). The "agents" responsible for each task are determined using the predefined table shown in Figure 3.3. For our example, the agent for evaluating the effect e = *effect on the housing geometry (Part = P0012)* will be "Designer of : P0012". The PLM system then directs the task to Pat, who is the actual designer of Part P0012.

Pat will then evaluate the effects of the change in joint on the housing geometry and describe them in a report. Ideally, the report created for any task will include information about any changes in parameter values, any additional changes required to accommodate the original change, as well as the impacts - in terms of the estimated costs of making these changes, time required to implement the changes, etc. These reports are stored and associated with the corresponding task in the workflow. If any additional change is required to accommodate the parent change, it might have its own downstream effects. The agent will therefore instantiate their change identifying its CT, and create new tasks in the workflow to evaluate its effects, in a process identical to the EC coordinator. In our example, Pat decides that the geometry of the housing will need to be changed. He classifies the change as belonging to CT = *part geometry change*. He defines attributes of the change instance, and creates further tasks in the workflow for potential effects prompted by the system, namely, effect on the manufacturing process of the housing, raw material required, etc. (see Figure 3.2(c)). In case no additional changes are required, e.g., when evaluating

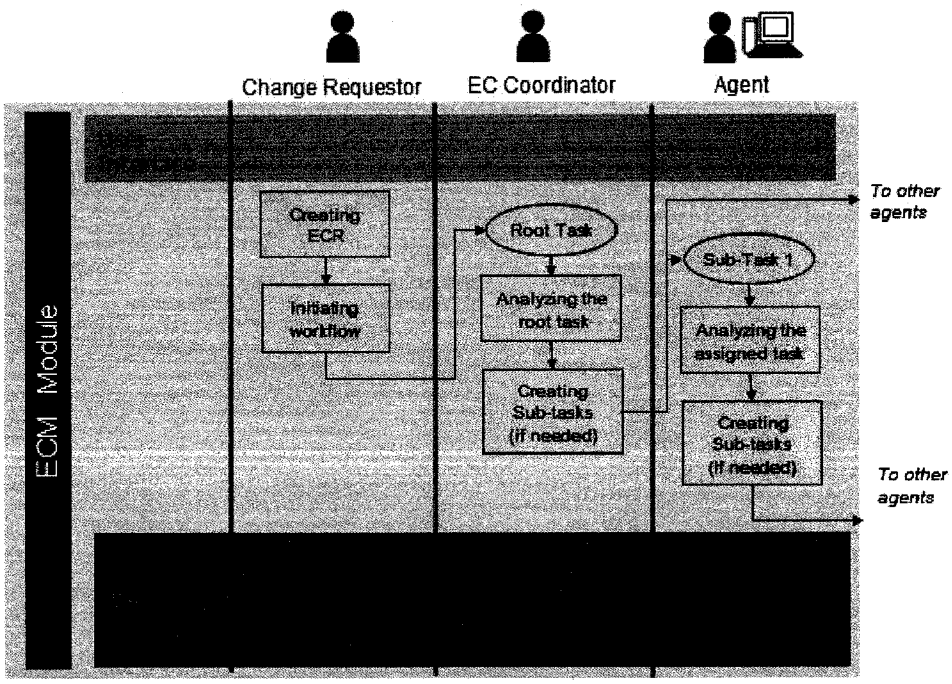


Figure 3.4: The process of creating the workflow

effect e = *effect on assembly weight* it is found that no modifications are required to accommodate the changed weight, the agent will merely submit a report and there will be no further tasks in the workflow. Once all the cascaded tasks are completed, the EC coordinator can compile all the reports to generate the final ECR evaluation report that is sent to the EC committee for approval.

In this manner, the tree-like workflow for the comprehensive evaluation of the ECR is developed dynamically. We shall refer to this workflow as the *change-effect tree.* Figure 3.4 shows a schematic of the process of generating the workflow for change evaluation. Such a workflow within a PLM system can also allow the EC coordinator to track the progress of the evaluation process.

3.4.1 Terms and concepts

Before we extend the above method further, we shall define the terms that we will be using in the following sections. A *task* refers to a node in the *change-effect tree* workflow. An *agent* is the individual or software program responsible for completing a *task*. For any *task*, the *agent* determines the changes (if any) that need to be made to the part, process or document that is being studied. Each such change instance is classified into one of the predefined *change-types (CTs)*. The *agent* also creates a *report* describing the required changes and the engineering and business impact, i.e., costs of implementing changes, time and resources required for implementation, etc. An *effect (e)* refers to any one of the possible effects (*set* E) that are predefined for the CT of the change made. The *agent* makes new *tasks* in the workflow to study each *effect* $e \in E$ of any additional change that he has instantiated. For example, consider figure 3.5 on the next page, which shows a portion of a *change-effect tree.* Jean is the agent for task t_0, which requires her to study the effects of an ECR on a valve cover she has designed. She decides that the shape of the valve cover will need to be changed and instantiates this change. Since this change belongs to $CT =$ *part geometry change*, she gets prompted about the three predefined effects $(e_1, e_2, \& e_3)$ as shown in the box on the left. Subsequently, she creates three new tasks $(t_1, t_2, \& t_3)$ in the *change-effect tree* workflow to study the effects and the system assigns them to the correct individuals.

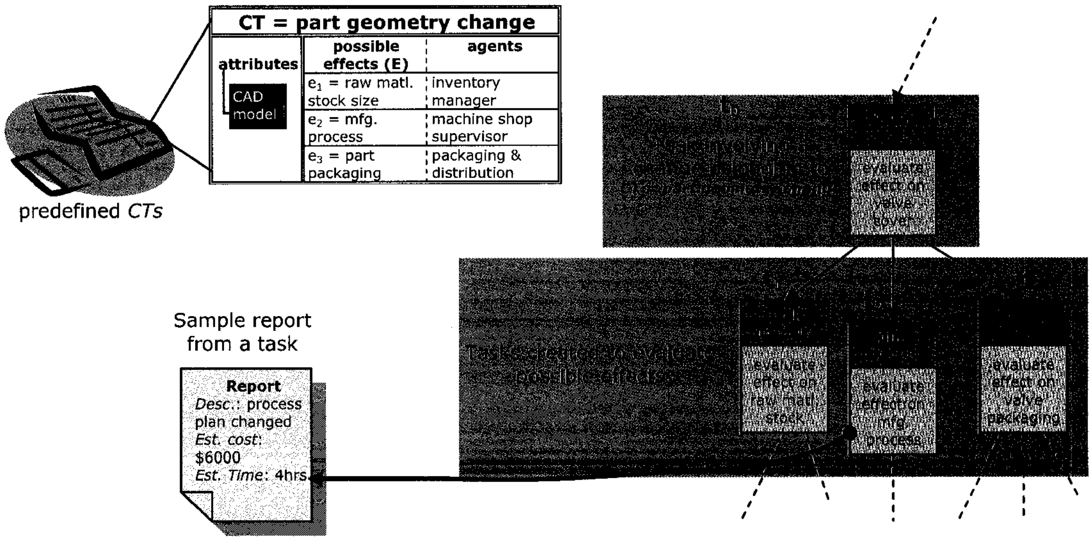


Figure 3.5: Terminology used in the proposed ECR evaluation method

3.5 Prioritization of effects using past knowledge

While the method described in section 3.4 enables detailed and comprehensive evaluation of the cascaded effects of an ECR, it is fairly tedious and time consuming. Such a detailed evaluation can certainly not be justified in case of minor changes or when the requested change needs urgent approval. For most changes, only certain effects are likely to present bottlenecks or impacts that must be evaluated prior to its approval, while the remaining effects are negligible. The ability to identify these important effects for a given change request requires detailed knowledge of the product and changes made to it in the past.

Consequently, to enhance the proposed ECR evaluation method, this experience has to be imparted to the change management system. When a change is instantiated the system must not only prompt the agent about the possible effects, but also use information from past ECs to generate advise about which of the effects are important and must be studied prior to approval. Using this advice, the agent can facilitate the evaluation process by creating new tasks for evaluating only the important effects. The other effects can be regarded as insignificant and eliminated from consideration, or evaluated later if specifically requested by the approval committee.

The basic idea used to predict important effects is that similar changes are likely to have similar effects. For example, if a change is made to a molded cover of one cell phone model, it is likely to have the same effects as a similar change made for another cell phone model. If there were significant effects on the dashboard manufacturing process, electrical wiring process, and assembly procedures, when the dashboard display layout was modified in the past, it is likely that the same effects will be significant if it is modified again. Thus, by analyzing the change-effect-trees for the similar change instances, we can determine which effects of the current change instance are important and must be studied.

In order to achieve this, we need to develop two key functionalities, viz.

1. the ability, given a change instance, to search a database of past ECs to find similar change instances; and
2. the ability to classify the effects of a previously studied change instance into important and negligible.

In the following paragraphs, we discuss the important factors that need to be considered to develop these functionalities and explain the approach being used in this research.

3.5.1 Comparison of change instances

Given the description of a change instance, the objective of this step is to identify change instances studied in the past that are most similar to the change instance under consideration. As stated before, change instances are defined by their attributes. All change instances of the same *CT* will have the same list of attributes. Thus, we can search through the knowledge base of previously studied ECRs for change instances with the same *CT*, and then further find the most similar instances based on a comparison of the attribute values.

It should be noted that different *CTs* have different attributes and the total number of attributes used in the ECM system can be extremely high. Developing comparison metrics for all possible attributes is beyond the scope of this paper. However, we shall consider in this paper three important attributes that will be common to all *CTs*, namely;

1. Part being changed
2. Reasons for proposed change
3. Assembly (functional unit) containing part being changed

Part being changed

Traditionally, similarity between two parts has often been calculated by comparing the geometric CAD models of the two parts. The geometry of the part is believed to implicitly contain all information about the part. Cardone, et. al. [40] provides a survey of methods to calculate shape similarity between parts. However, the effects of a change to a part often derive from factors such as machining centers or facilities used to produce the part (e.g., paint shop, furnace, mill-turn), other parts in the vicinity, properties of the material (e.g., conductivity, recyclability), fixtures, palettes, or other material handling equipment used, etc. These cannot be inferred merely based on the geometry of the part. Such information is presently stored in various unlinked documents, namely, Bills of Material, process plans, factory layouts, workflow diagrams, etc. However, PLM systems allow efficient linking of these documents, such that all information related to the part can be readily obtained. Therefore, it is preferable to consider all factors while comparing the "Part being changed" attribute.

Consideration of all disparate factors to calculate a common similarity measure presents the following challenges;

1. *Factors have different characteristics and incompatible representation schemes:* For example, 'machine use' may be represented by Boolean variables (used - not used), 'recyclability' may be classified using fuzzy variables (easy - difficult - not recyclable), 'conductivity' is recorded as a continuous variable, 'shape' is usually recorded as B-Rep CAD models, and so on. For factors such as 'hardness' different scales are used for reporting the property in different materials and no direct correlation exists between the different scales.

2. *The "level of detail" required while comparing each factor needs to be established:* For example, one needs to decide whether to use a broad classification into conducting and non-conducting materials OR to use numerical conductivity

values while comparing two parts being changed. Similarly, one needs to decide whether it is sufficient to note that a 'lathe' is used during machining of the part, OR whether the number of turning/threading/boring operations and their times should also be noted.

3. *Interactions and inter-relations between factors need to be identified:* The similarity measure should be able to give more weight to combinations of factors (e.g., electrical components close to flammable parts, OR parts that require further machining after hardening) that are likely to cause important effects when the parts are changed. At the same time, the measure should avoid bias generated by double-counting when certain factors always appear together (e.g., all parts that use the furnace also use the cooling chamber).

4. *Weights to be given to different factors in the calculation of similarity need to be established:* Certain factors are more likely than others to lead to effects when parts are changed and thus different weights should be attached to the different factors while comparing the parts being changed.

To determine of "level of detail" to be used for any factor, the trade-off between the incremental benefit of increasing the "level of detail" (i.e., the accuracy in finding similar change instances) and the incremental computational costs will have to be considered. These benefits and computational costs will depend upon the nature and size of the company. In our preliminary work, we do not study the effects of changing the "level of detail" used.

In this research, we represent the part being changed with a help of a binary string or word. This is a high-level representation of the part wherein each bit encodes a characteristic (e.g., whether the lathe is used for manufacturing) or property (e.g., whether it is a precision part) of the part being changed. The "level of detail" encoded in this representation can be increased by using more bits for respective characteristics.

The characteristics encoded in the binary string representation are classified into four categories, viz.:- properties of the part, manufacturing facilities required to make part, production equipment required in production of part, and the context in which the part is used in the final product. Using the binary string representation, two parts being changed can be compared using a Jaccard coefficient. Thus, for any two parts A and B, the similarity is given by

$$\begin{aligned} Sim\left(A,B\right) &= \frac{\text{number of characteristics that are TRUE in both } A \text{ and } B}{\text{number of characteristics that are TRUE in at least one part } A \text{ or } B} \\ &= \frac{n\left(A \bigcap B\right)}{n\left(A \bigcup B\right)} \qquad (3.1) \end{aligned}$$

The complete list of characteristics used for the example case of the valve manufacturer is shown in Table 3.2. Table 3.2 also shows the binary strings for two components, namely, the "housing" and the "cover" of the valve example. The similarity calculated between these two parts is 0.625.

The above method does not capture inter-relations or interactions between factors. Incorporation of this aspect requires detailed analysis of engineering changes and their effects in the domain or company using this method, and is beyond the scope of this work. Similarly, the weights to be assigned to different factors can also

Table 3.2: Example of binary string representation used for comparing "part being changed" attribute

Category	**Characteristic**	*housing*	*cover*
Property of part	Size (Is is Large ?)	0	0
	Weight (Is it heavy ?)	0	0
	Shape (Is it intricate ?)	1	0
	Accuracy (Is it a precision part ?)	1	1
	Regulated component ?	1	1
	Recyclable	1	1
	Good Conductor	1	1
	Hardness (>5 on Mohs' scale ?)	1	1
Manufacturing facilities used	Lathe	0	1
	Milling machine	1	0
	Furnace	1	1
	Electroplating tank	1	0
	Paint booth	1	1
Production equipment used	conveyor 1	1	0
	conveyor 2	0	1
	assembly fixture	1	1
	Painting fixture A	1	1
	Painting fixture B	0	0
Context (parts in vicinity)	valve and actuator unit	1	1
	pump motor assembly	0	0

be decided by the company.

Reasons for proposed change

Presently, there is no commonly accepted representation or standard for recording reasons for a proposed change in an ECR. Such reasons are usually entered manually using natural language. Direct application keyword matching or other techniques to ascertain semantic equivalence in natural language statements is difficult, and depends on the correct interpretation of the language used.

On the other hand, considerable literature is available on the methods for recording reasons behind design decisions, or the "design rationale". Design rationale systems have been classified into "history-based", "process-based", "argumentation-based", "device based", and "active document based" systems, although these are not mutually exclusive types [41] . In this research we use the basic framework of an argumentation-based system, namely the IBIS (Issue Based Information System) proposed by Kunz and Rittel [42], to represent reasons for change. This system considers design decisions as *Issues* that need to be addressed. The different options available to the designers are *Positions* that respond to those *Issues.* Finally, there are *Arguments* that support or object-to the *Positions.* Conklin and Begeman [43] further developed a hypertext prototype called gIBIS (graphical IBIS) to support Rittel's IBIS method.

In the strict sense, an ECR is a request to change from one chosen *Position* on a design *Issue* to another *Position.* This may be due to availability of a new option/*Position*, or changes/additions in the *Arguments.* However, at the ECR stage

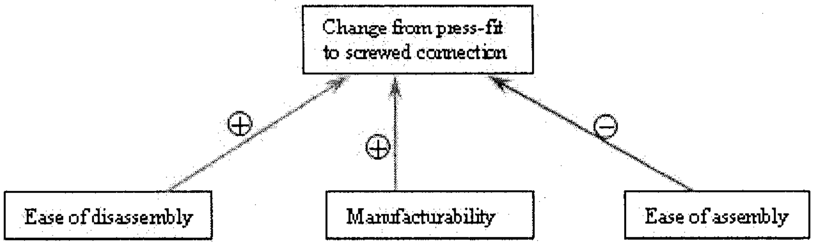


Figure 3.6: Representation of "reasons for change" for example case of change in joint

the only decision to be made is whether or not to recommend the change. Therefore, it is beneficial to simply model the proposed change as a *Position* and the reasons for the change as the *Arguments* that "support" the *Position.* Any anticipated disadvantages will be recorded as *Arguments* that "object-to" the *Position.* In this way, only those design considerations that govern the change are accounted for. This representation can also be used to update the "design rationale" if the change is approved.

For example, consider a change in a joint from a press fit to a screw connection (as in the valve example) to increase "ease of disassembly" and "ease of manufacturing" (since there is no need for close tolerances). Let us assume that the requester anticipates a disadvantage of the change, namely increased assembly time to drive in the screws. The corresponding *Argument* is named "ease of assembly". In that case, the reasons for proposed change would be recorded as shown in Figure 3.6, where the +ve sign indicates that the *Argument* "supports" the *Position* while the -ve sign indicates that the *Argument* "objects-to" the *Position.*

Thus, the reasons for a requested change can be formally represented by a set of pairs, where the first element of the pair is the *Argument* and the second element is its relation (i.e., whether it "supports" or "objects-to") with the *Position.* In order to prevent different natural language descriptions for the same *Argument*, we require the *Arguments* to be chosen from a predefined list.

We have already seen the use of the Jaccard Coefficient to calculate similarity for "parts being changed". We employ a simple modification of the Jaccard Coefficient to account for the fact that each element in the sets now has a qualifier that can take either of two values, namely "supports" or "objects-to". Consider, sets A and B contain the "reasons for change" for the two change instances being compared. Then the similarity of the attribute "reasons for change" for the change instances is given by,

$$Sim\left(A,B\right)=\frac{n\left(A_s\bigcap B_s\right)+n\left(A_o\bigcap B_o\right)}{n\left(A\bigcap B\right)} \tag{3.2}$$

where $n\left(X\right)$ = number of elements in set X

$X_s = \{a|a \in X$ and a "supports" requested change$\}$

$X_o = \{a|a \in X$ and a "objects-to" requested change$\}$

Assembly containing part being changed

Any product is sub-divided into functional units or assemblies, which interact with each other only at the designed interfaces. For example, a cell phone can be divided into cover assembly, keypad assembly, display assembly, main PCB and SIM card, and battery. An automobile, on the other hand, can be divided into chassis, body, electronics, and drive-train; where the chassis can be further divided rear axle assembly, front axle assembly, and frame; and so on, leading to a hierarchical classification of functional units.

Since this classification is fixed for any given product, similarity between any two classes, i.e. assemblies, can be predefined by human experts. For example, the similarity of the front axle assembly with itself will be 1, while the similarity between the front axle assembly and the rear axle assembly will be less than one, but higher than the similarity between the front axle assembly and the gear box. Accordingly, a look-up table can be created defining the similarity for all pairs of functional units. For any two change instances, the similarity for the attribute "Assembly containing part being changed" can be readily obtained from the look-up table.

This method of using predefined look-up tables is also applicable for any attributes which can take only one value from a finite predefined list. For example, in case of CT = *Change in material of part*, the original material and new material attributes can be compared in this manner. Likewise, look-up tables can also be used for comparing the original joint type and the new joint type attributes in case of CT = *part connectivity change.*

3.5.2 Identification of significant effects

The aim of finding similar past change instances is to determine which effects, among the predefined list of effects (E) for the particular CT, are important and should be evaluated further. For this purpose, for every similar change instance identified, the reports of subsequent tasks in the corresponding change-effect tree are studied to classify its effects into "significant" and "insignificant".

The decision to approve or reject a proposed EC is made after evaluating different types of impacts, such as cost and time required to implement the change, change

Table 3.3: Impact categories considered during approval of a change

Category	**Sub-category**
Production impacts	Setup/implementation costs Time required for setup/implementation Change in operating costs Change in production cycle time
Service impacts	Training and documentation costs Expected change in maintenance/disposal costs
Sales impacts	Expected change in price of product Expected change in sales
Environmental impacts	Human health Resource Depletion Ecosystem impacts
Strategic impacts	Impact on product image Impact on supplier relationships Impact on long term goals of company

in operating costs or production cycle times, expected returns (in terms of increased sales), documentation and training requirements, etc. Additionally, in case of major changes certain intractable factors, such as environmental impacts, impacts on supplier relations, etc., are also considered. Table 3.3 lists the various types of impacts considered during approval of an EC.

In this research we limit our scope to consideration of only the production impacts. An effect is considered "significant" if it has any impact that would be substantial enough to influence the EC approval decision. Whether the magnitude of an impact is considered substantial also depends upon the prevailing conditions. For example, a long setup time may be given a lot of weight if the change needs to be urgently implemented, however the same setup time may be considered negligible if there is sufficient time before planned implementation. Therefore, we allow the user to define thresholds for each type of production impact, namely setup time

($ST_{threshold}$ man-hours), setup costs ($SC_{threshold}$ dollars), absolute change in production cycle time ($CT_{threshold}$ man-hours), and absolute change in operating costs per cycle ($CC_{threshold}$ dollars), beyond which an impact will be considered substantial. Such separate thresholds for each impact category avoids the problem of a substantial impact being averaged out by insignificant impacts in other categories. These thresholds can be defined by the EC coordinator, or can be set by the PLM system administrator and updated at regular intervals.

To calculate the impact value in each category, we take the sum of the impact values (in the said category) recorded in the reports of the task corresponding to the effect and all its child-tasks in the change-effect tree. Thus, if ST_e is the net setup time, SC_e is the net setup cost, CT_e is the net change in production cycle time, and CC_e is the net change in operating costs, attributable to a particular effect e, then e will be classified as "significant" if

$$(ST_e \geq ST_{threshold})\, or\, (CT_e \geq CT_{threshold})\, or\, (SC_e \geq SC_{threshold})\, or\, (CC_e \geq CC_{threshold})$$

3.5.3 Generating advice for the user

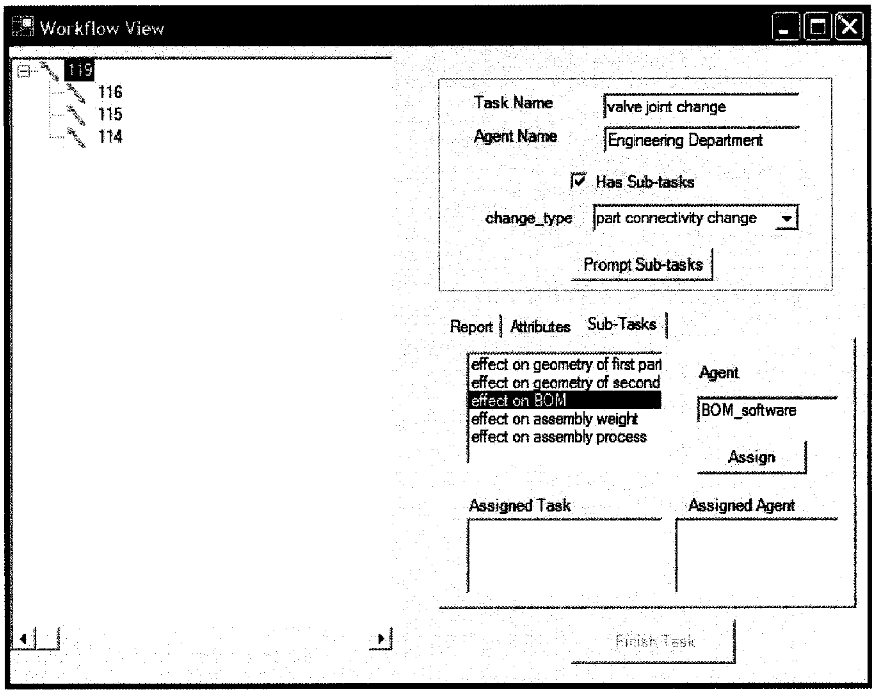
Once similar change instances have been identified and their effects have been classified into "significant" or "insignificant", the system uses a simple voting method to suggest the priority of evaluating each effect for the current change task.

Consider that a change instance belonging to a particular CT has been created during evaluation of some ECR. Using the comparison metrics discussed earlier, N most similar previous change instances are determined for each attribute used to describe the change instance. Thus, if there are m attributes describing the CT, then we have $m \times N$ similar change instances. Note that this allows for change instances to be double counted if they are similar to the current change instance with respect to two or more attributes. However, this prevents change instances which are very similar with respect to one attribute from being overlooked due to differences in other attributes. For example, if changes to any part using the paint booth require significant setup times, this effect should not be neglected irrespective of the reasons for initiating the change or the parent assembly.

Thereafter, for each effect, among the predefined list of effects (E) for the particular CT, we award one "vote" for every similar change instance wherein that effect is classified as "significant". If the effect had not been evaluated in a particular change instance it is considered to be "insignificant". If any effect gets more than a predetermined threshold K (where $K < N$) "votes", it is likely to be important for the current change instance and the user is prompted to create new tasks to study that effect. The thresholds K and N are determined by the company based on the number and diversity of previous change instances stored in their knowledge bases. The condition ($K < N$) ensures that some effect is not neglected if it is significant only in change instances matching in one specific attribute.

3.6 Implementation

Currently available PLM solutions do not allow dynamic editing of a workflow process by users. To serve as a demonstration of our method, we have developed a stand-alone implementation for our method using VB.NET and a MS Access database server. A custom form is provided for initiating an ECR. The form requires the



Task Name: valve joint change
Agent Name: Engineering Department
☑ Has Sub-tasks
change_type: part connectivity change

effect on geometry of first part
effect on geometry of second
effect on BOM
effect on assembly weight
effect on assembly process

Agent: BOM_software

Figure 3.7: Agent interface in workflow

user to provide information about the part being changed and its parent product and subassembly. Other information such as “date of request”, “description of change”, etc. is also included. Once submitted, the system automatically assigns it a unique ECR number. For the purpose of evaluating the proposed change, a workflow process is initiated. A root task is created in the workflow, describing the proposed change, and is assigned to the designated EC coordinator (agent).

The interface available to the agents is shown in Figure 3.7. The left pane shows the current workflow structure as a tree of tasks, where each task is presently identified by a unique task number. Upon selecting a task in the workflow, the right pane is activated. A user with the required permissions (i.e., the agent assigned to that task) can add attributes and submit his evaluation report. If the task involves a change that can have further effects, the agent can specify the *change-type* and is prompted of the possible effects of the change. The agent can then create subtasks, by selecting important effects and assigning corresponding agents for those tasks. The agent can indicate that his task has been completed, by clicking the "Finish Task" button. Once a task is completed, it cannot be edited, and its subtasks become active. All information about each task, such as attributes, reports, subtasks, etc., is stored in an Access database. At present, the algorithms for prioritizing the evaluation of effects are implemented separately and have not been integrated into this implementation.

3.7 Limitations and Future Work

In our implementation, we have used a limited set of predefined *CTs*. A practical implementation will require the organization to create a well-defined taxonomy of *CTs*, and the initial database enlisting the required attributes (A) and possible effects (E) for each *CT*. Such a classification will depend upon factors such as complexity and variety of products manufactured, organizational structure of the company, expected life-span of product models, etc. The effectiveness of the method will depend on the suitability of the classification for the particular industry or organization. However, we believe that over time sufficient experience will be generated to arrive at the most suitable and comprehensive classification.

One advantage of this framework is that it allows for the taxonomy and knowledge-base to be built and refined over time, such that new *CTs* or unanticipated effects identified can be incorporated. This will allow companies to implement this method in a controlled manner and validate the anticipated benefits, before completing a full scale implementation. Such a validation study would also provide insights towards developing a suitable list of *CTs*, as well as choosing appropriate thresholds.

In this research, we have developed similarity measures for certain common attributes, with the aim of finding past cases with similar change instances. As the size of the taxonomy increases, additional attributes will be used to define each *CT*, and consequently similarity measures will need to be developed to compare those attributes. However, the basic principles of formulating the similarity measure shall be the same. As discussed in section 3.5, the development of similarity measures for change instances and the calculation of impacts attributable to effects presented several issues involving trade-offs between the complexity of the calculation and the benefits of increasing the accuracy of the measure. Further study of these issues, using information from practical EC cases, will help refinement of the measures used.

The current method used to evaluate the importance of an effect takes into account the production impacts, i.e., cost and time requirements attributable to the effect. Further research is required to develop techniques that account for sales, environmental and strategic impacts when calculating the importance of an effect. Secondly, over time there may be changes in the processes, or economic factors that contributed to the production impact of the previous change instance. For example, an increase in labor rates might transform minor effects in past change instances into significant effects for the current change instance. The current method does not make provisions for such cases. In order to take such considerations into account, new methods will be required to adjust the calculated impacts using information about the source of the impacts.

Finally, prioritization of effects is carried out by studying a predefined number of similar change instances. This assumes that sufficient number of similar past change instances are available. Depending upon the nature of the requested change, the number of similar past instance may be larger or lower than the preset number used. This implies that some relevant similar change instances may be neglected, or that the instances used may not be sufficiently similar. Approaches that vary the number of similar change instances considered or normalize the calculated impacts with respect to the similarity between the change instances should be studied to improve the prioritization step. Experience and cases studies will also be required to enable users to define appropriate thresholds used at various points in the prioritization of effects.

It will also be interesting to further extend the method presented here to accommodate common industry practices, such as consolidation of different ECRs into a single ECR, and ECRs involving changes to multiple parts or processes. Extensions to account for effects on a single part or process due to multiple simultaneous ECRs will also be useful. Many organizations often handle Problem Reports (PR) by the same process as ECRs. Further research will be required to enable simultaneous evaluation of different solution approaches to a reported problem, or different modifications that can be made to accommodate a requested change.

CHAPTER IV

Identification and characterization of joints in CAD assembly models

As discussed in chapter I, it is important for original equipment manufacturers (OEMs) to design components such that alternate end-of-life treatment options are available, and the best treatment plan can be chosen on a case-by-case basis depending upon local resources, market conditions and condition of incoming end-of-life parts. In this chapter, we describe a framework that will enable such case based selection of the treatment plan. We also present our work toward developing a key capability, namely the identification and characterization of joints in CAD assembly models, that will ease integration of the described framework with existing CAD and PLM systems.

4.1 Motivation

Traditionally, the processing of used and discarded products has been a small-scale, profit-driven activity restricted to junk-yards or certain material-specific recycling units. Consequently, most products ended up being land-filled or incinerated at municipal disposal sites. However, upcoming regulations force OEMs to take back their end-of-life products, either directly or in partnership with authorized treatment facilities (ATFs), and process them, with requirements on amounts of material to be recovered and recycled, and strict guidelines on separation and treatment of hazardous substances.

Since the financial burden of this activity is to be borne by the OEMs, it is important for OEMs to plan the treatment process so as to optimize on the processing costs. But the feasibility and processing costs for a treatment plan depend upon many variable factors such as availability of local resources, markets for refurbished goods and recycled material, damage to incoming parts, local regulations, proximity of recycling/disposal facilities, local labor rates, etc. While deciding a treatment plan OEMs must take into account these variable factors, as well as fixed factors such as product configuration, material composition, locations of hazardous substances, minimum recovery and recycling requirements, etc.

Accounting for all such factors will undoubtedly require collaboration between various stakeholders in the enterprise. For example, suppliers need to provide detailed information about the material composition of their components, OEMs need to give detailed dismantling instructions, demand for refurbished components, alternate uses and recycling options, ATFs need to provide information about available tools and technologies, labor rates, etc. In addition, public knowledge-bases with information about regulations, market trends, etc., will also be needed. Therefore, a systematic method is required that can enable such collaboration, and decide the best treatment plan for each situation.

CAD assembly models are commonly used to store product configuration information in commercial PLM systems. While CAD models capture the relative positions of components of an assembly and sometimes kinematic relationships between the components, they do not capture joint information, such as the joining elements used, method of disengagement, tool required for disengagement, etc. However, this information will be required for any methodology to determine the end-of-life treatment plan. Manually supplying joint information in standardized, machine-readable formats is tedious and time consuming. This is especially true for products involving large number of parts and sub-assemblies that are designed by different stakeholders and are sold in a variety of different configurations. As a result, systematic automated methods are required to extract and characterize joint information from geometric CAD assembly models. While developing such a method, it should be noted that often times standard joining elements, such as screws, nuts & bolts, springs and bearings, are not modeled in CAD. Moreover, parts are modeled as rigid objects and joints obtained due to compliance of parts, such as snap fits, are difficult to identify.

4.2 Objective

The objective of this research phase is twofold:

1. To develop a systematic framework to enable case based selection of the optimal end-of-life treatment plan for a product; and
2. To develop methods to identify joints between components from geometric CAD assembly models, and characterize them with respect to type of joint,

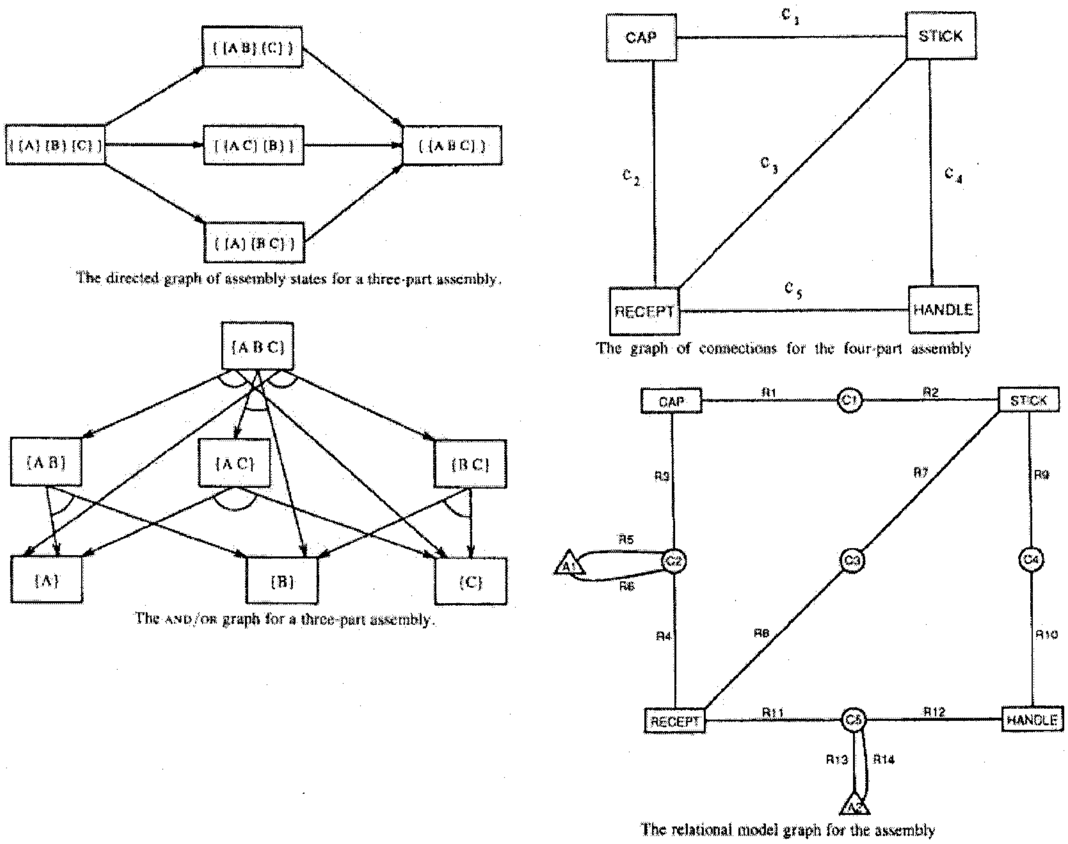
size, orientation, etc., to assist determination of tooling and accessibility requirements for disengagement.

4.3 Literature Review

Determination of an end-of-life treatment plan involves deciding the sequence of disassembly operations to be carried out, the end-fate (such as recycling, reuse, disposal) for each separated component or sub-assembly, and all the processing steps (such as cleaning, repair, shredding, safe storage and transportation to disposal site, etc.) to be completed on the components or sub-assembly before handing it over to another organization (such as a landfill, recycling unit, or a used parts vendor). In this section, we present a brief review of various approaches in literature that are relevant to different portions of this problem.

De Mello and Sanderson [44] use an AND/OR graph representation to generate a complete set of feasible assembly sequences. The feasibility of a sequence is decided by reasoning on a "relational model" of the assembly formed by adding attributes to the "graph of connections", as shown in Figure 4.1. The "relational model" includes information about types of connections and contacts between parts, their precedence relationships, etc., and is generated using information supplied by a human expert.

Desai and Mital [45] present a methodology for systematic application of Design for Disassembly (DfD). They calculate a time based numeric disassemblability evaluation score, giving weightages to ergonomic factors such as size or shape of component, weight, frequency of a type of task, postural requirement, etc. The score obtained for complete disassembly of the product into constituent parts is used to



The directed graph of assembly states for a three-part assembly.

The AND/OR graph for a three-part assembly.

The graph of connections for the four-part assembly

The relational model graph for the assembly

Figure 4.1: AND/OR graph and Relational Model for assemblies [44]

evaluate and improve product design. Gungor and Gupta [46] use the concept of "Total Time for Disassembly", another time based metric, to measure efficiency of a disassembly sequence. They provide a heuristic for generating the best sequence of disassembly operations, but require the user to define the operations and input precedence relationships and an average difficulty rating for each operation.

A number of authors have investigated methods to determine the sequence of disassembly operations and the optimal disassembly depth, to obtain maximum net revenue. Solution methods include graphical methods, empirical methods, simulated annealing, search algorithms and mathematical programming. Lambert presents the disassembly problem as a linear programming problem [47] in which the variables to be optimized determine whether a particular operation should be carried out. The cost of each operation, its technical feasibility and the returns expected at each state of disassembly have to be input manually. Chen, et al. [48] present a cost-benefit analysis to determine how much effort should be put into the disassembly and recycling of a product. Navin-Chandra [49] also presents a break-even analysis between the effort put into recovery of components and the effort saved by reusing parts and material using the traveling salesman methodology.

Subramani and Dewhurst [50] provide an algorithm to create a disassembly diagram by extracting precedence information from a user defined relation model, consisting of parts, contacts, attachments and relations. They then use a branch and bound algorithm to find the optimal path. Hula, et al. [51] use a genetic algorithm to find optimal disassembly sequences when precedence relationships are supplied by user as constraints. The fitness function used also gives consideration to different cost structures and environmental impacts in different geographical regions of the world. Bras and Emblemsvåg [52] study the economics of disassembly under uncertain conditions using activity based modeling.

All approaches discussed above use a more sophisticated representation of the assembly models than is directly available from CAD software. Graph representations or combined graph and matrix representations are popularly used [53]. These representations incorporate information such as sub-assembly parent-child relationships, part contacts, joint and fastener types, disassembly tool, time for disassembly operation, precedence of operations, component weight and material, etc. Consequently, these approaches require manual intervention to define joints, fastener types, tools or component accessibility and precedence relationships between operations.

Manually defining this information, although possible, is often repetitive and time consuming. Also, the task of visualizing accessibility of joints is often difficult and unintuitive in the absence of a physical model. Mo, et al. [54] present a virtual reality based disassembly analyzer that assists the user in generating assembly relation information. It creates an accessibility graph and a removability graph. However, use of virtual reality cannot ensure that all possible methods of accessing the joints have been considered by the human user.

Woo and Dutta [55] study the accessibility of assembly components themselves, in terms of the number of unidirectional motions (m) required to remove a component from the assembly. The component is then said to be $m-disassemblable$.

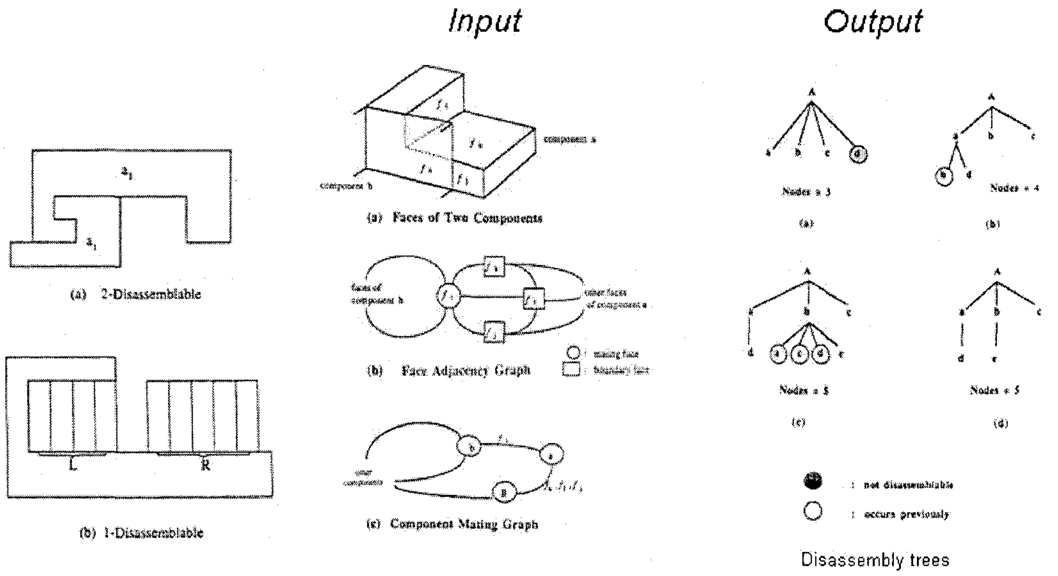


Figure 4.2: $m-disassemblable$ components and generation of "disassembly tree" [55]

They present an algorithm that uses the Face Adjacency Graph and a related "Component Mating Graph" to form a tree of feasible disassembly sequences, as shown in Figure 4.2. The algorithm can determine the disassembly sequence for a totally ordered assembly with $1-disassemblable$ components. Joints between components are not considered at all.

Accessibility of a point in an assembly has also been studied for off-line generation of robotic motion paths for industrial welding robots. Ting, et al. [56] use distance maps to detect obstacle collision. A wave expansion method or a depth first search is used to search for the best collision free path. Ranjan, et al. [57] also employ virtual reality to analyze accessibility of assembly after welding jigs are attached.

4.4 Framework for selection of end-of-life treatment plan

In this section, we describe a consolidated framework within PLM for case-by-case selection of the treatment plan for incoming end-of-life products. The framework builds upon the approaches discussed in the previous section. For the purpose of the framework, we suggest an efficient, graphical representation, called the *partition lattice* [58], to model the problem. Consider a product assembly made up of n indivisible components or parts, labeled $1, 2, ..., n$. Then, the partition lattice π_n represents all possible ways in which the product can be separated into parts and sub-assemblies. For example, Figure 4.3 shows the partition lattice π_4 for a product with four parts. Each node of the lattice is a partitioning (i.e., a set of subsets which have no common elements and includes all elements in the parent set) of the set $\{1, 2, ..., n\}$. Thus we can consider each node as representing a state of disassembly, wherein all components in a partition are considered to be contiguous forming a sub-assembly. Correspondingly, each edge of the lattice represents a disassembly operation, separating one set in the partitioning into two smaller subsets to get a new partitioning.

Given this representation, choosing the disassembly operations to be performed and their sequence corresponds to choosing the path on the lattice that begins at the root node (completely assembled state) and ends at any other node on the lattice. The end node of this chosen path represents the final disassembly state (sometimes referred to as disassembly depth), beyond which any remaining sub-assemblies will not be further separated into components. The end-fates of the separate components

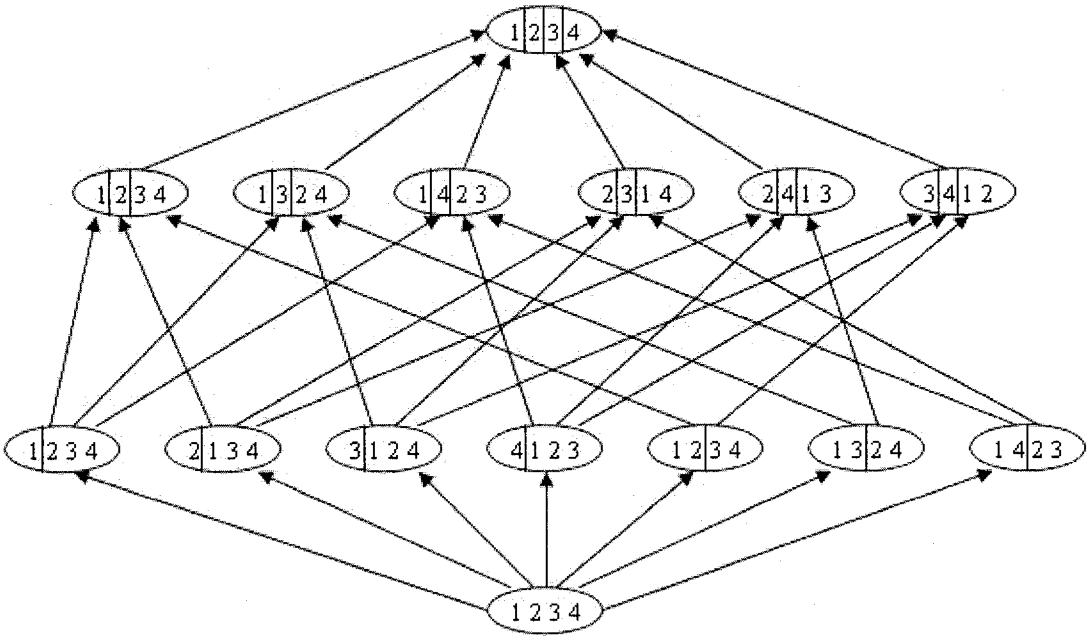


Figure 4.3: Partition lattice (π_4) for a four part product

and sub-assemblies at this stage, and the intermediate processing steps required, must also be decided.

The framework described below essentially involves adding information to this model, namely costs for each disassembly operation (or edge in the lattice) and the costs of processing components and returns from refurbishment or recycling at each state of disassembly (or node in the lattice), so as to enable selection of the optimal treatment plan (or path in the lattice). Additionally, regulatory requirements are added as constraints on allowable final disassembly states. The steps involved (as shown in Figure 4.4) are explained below:

1. *Determination of possible end-fates and corresponding processing requirements for each possible sub-assembly and component*

   For any product assembly with n indivisible components, there are $2^n - 1$ pos-

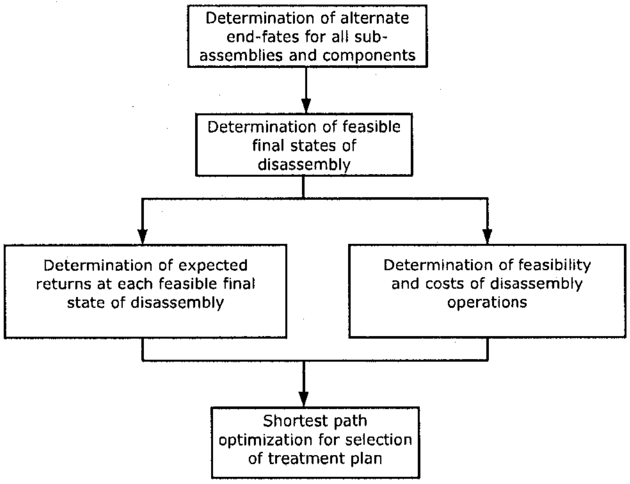


Figure 4.4: Tasks in planning end-of-life treatment strategy

sible subsets or sub-assemblies (not including the null set ϕ). For each such sub-assembly, the designers must define all alternative end-fates and corresponding processing steps, such that no regulations (e.g., disposal of hazardous materials) are violated and no further non-destructive disassembly of the sub-assembly is carried out. If a sub-assembly, as defined by a subset of $\{1, 2, ...n\}$, cannot be realized (e.g., if it contains components that are not connected) the sub-assembly should be marked as "infeasible". A sub-assembly is marked "ineligible" if there is a legal requirement to further disassemble the sub-assembly and a single end-fate cannot be defined (e.g., if it contains substances that have to be disposed separately).

Consequently, this phase requires inputs from design and recycling experts, to define all possible end-fates. Inputs from individual suppliers is required for information about material compositions and locations of hazardous substances. Knowledge about applicable global and local regulations is also required and can either be sourced from public databases or supplied by the ATFs. Knowledge about local processing capabilities should also be provided by the ATFs.

2. *Determination of feasible final states of disassembly*

   The next step is to determine feasible final states of disassembly. Each node of the partition lattice defines a state of disassembly, and is composed of a combination of sub-assemblies and components considered in the first step. Thus, any node in the lattice can be a feasible final state of disassembly if;

   - No sub-assembly in the partitioning for the node is marked as "infeasible" or "ineligible", and
   - There exists at least one combination of available end-fates for the sub-assemblies and components, such that all regulations for minimum recovery of components, minimum recycling of material, and separation and safe handling of hazardous materials, are satisfied.

   Thus, this step requires input about applicable product level regulations and a method to validate the combinations of alternate end-fates against these regulations.

3. *Determination of expected returns at each feasible final state of disassembly*

   Once feasible final states of disassembly are determined, one must find out the expected returns if the given node is chosen as the final state of disassembly. For a given state of disassembly, multiple feasible combinations of end-fates of the components may exist. Therefore, at this stage, costs for processing steps such as degreasing, cleaning, transportation, etc., must be provided by the ATFs. Similarly, expected returns from recycling or refurbishment and costs of disposal must also be calculated. The condition of incoming parts must be provided by the ATFs at this stage, since the expected returns may be affected if a part is damaged.

Using this information, the combination of end-fates for components and sub-assemblies, that gives maximum returns must be found for each feasible final state of disassembly and the corresponding value of expected returns must be associated with the respective nodes in the partition lattice.

4. *Determination of feasibility and costs of disassembly operations*

In order to select the optimal path in the partition lattice, one must first find feasible edges (i.e., feasible disassembly operations) and the costs associated with them. Each edge in the partition lattice represents a disassembly operation that divides one subset/sub-assembly into two smaller subsets/sub-assemblies (or components). The edge will be regarded as feasible, if the resulting sub-assemblies are "feasible" (i.e., contiguous) and if the joint holding the two sub-assemblies together is accessible in the parent sub-assembly. For a feasible operation, the cost of performing the operation needs to be calculated and assigned to the edge. For infeasible operations the corresponding edge is removed from the solution space. It should be noted that consequently, any node that has a sub-assembly that is marked "infeasible" shall automatically be removed from the solution space.

This step involves locating joints, determining tools required to disengage the joints, determining accessibility of joints and a collision free path to isolate the sub-assemblies, and lastly, the time, effort and costs of disengaging the joints. These tasks require knowledge of the structure and geometry of the assembly, and the ability to extract information about joints from this information. Information about damage to any part (leading to need for special tools or fixturing), missing parts (leading to easier access to a joint), and existing labor rates, will also be necessary to obtain the accurate feasibility and cost estimates for the disassembly operations.

5. *Optimization for selecting optimal treatment plan*

   The final step in the framework involves optimization to select the optimal treatment plan (i.e., the optimal path and final processing steps corresponding to the final state of disassembly). This essentially involves solving a one-to-many shortest path problem on the partition lattice for paths starting at the root node and ending at any of the feasible final states of disassembly.

The framework described above reduces the decision about the end-of-life treatment strategy to the solution of a shortest path optimization problem. This framework affords the flexibility to decide the treatment strategy dynamically taking into account temporal and local considerations, such as prevailing markets, labor costs, facilities available, as well as the condition of incoming products. There are various methods discussed in literature for solving such optimization problems.

Development of a customized solution algorithm is beyond the scope of this research. The main challenge in using this framework lies in setting up the optimization problem for each product configuration. In this research, we focus our attention on Step 4 of the framework, particularly, on the identification and characterization of joints in order to determine costs, time, and effort of disengagement.

4.5 Identification of Joints

As discussed in section 4.3, previous approaches for disassembly planning have used special representations of assembly models wherein information about joints is entered either by a human expert or using external techniques such as virtual reality.

In an integrated PLM framework, information about joints must be extracted from CAD models, which constitute the primary format for storing product configuration information. Current CAD formats do not store information about joints explicitly. However, efforts are underway to develop schemas to represent assembly information [59], such as mating constraints and connections in CAD. Even so, deduction of joint information from geometry will be useful for detecting designer's intent and assisting the definition of joints; and for ensuring consistency between geometry and stored joint information as the geometry undergoes modifications during the evolution of the design.

Although standard joining elements are seldom modeled in CAD, certain geometric features are often present on the modeled components that will betray the existence of a joint between them. For example, a single hole on one component being aligned with another hole (or holes) with the same nominal diameter on the other component indicates the likelihood of a pinned joint between the two, whereas an array of such aligned holes indicates a likely rigid connection using nuts and bolts or screws. Similarly, beveled edges at the mating faces of aligned plates are usually designed in case of a welded joint.

Therefore, our approach in this research is to determine the required geometric features on the mating components and their position and orientations relative to each other, to indicate the presence of a particular of type joint. We then implement heuristic and rule-based algorithms to search for these conditions in the CAD assembly models. We further characterize identified joints by determining the dimensions, orientations, etc. of these features. This will enable identification of the tool required to release the joint and direction of approach for the tool. Using this information, one will be able to verify the accessibility of the joint in any given sub-assembly configuration. We limit the scope of our research to two of the most commonly used joining methods, namely, threaded fastener joints and snap fits.

We make the following assumptions about the input CAD models:

- The assembly is modeled as a collection of individual parts. B-Rep representations are available for individual parts positioned in the assembled configuration in a common coordinate frame.
- Joining elements (such as, screws or bolts) may or may not be modeled. However, the parts being joined are modeled completely, i.e., the holes to locate fasteners or pins are modeled.
- Threaded holes are modeled as simple holes without threading.

4.5.1 Identification of joints using threaded fasteners

The two basic types of commonly used threaded fasteners are "nuts & bolts" and "screws". Nuts & bolts are generally used with pre-drilled simple holes. Access from both sides of the component during assembly or disassembly is generally required. A screw (or a bolt without a nut) passes through a simple hole in one component and fits into a threaded hole in the other. Screws and bolts are variously classified depending upon thread pitch (coarse/fine), hardness grades, type of head (flathead or countersunk, buttonhead, hexagonal head), type of screw drive (slotted, cross head, hexagonal head, torx head), etc.

For the purpose of this research, we only distinguish between "nut & bolt" joints and "screw" joints. Apart from flathead (i.e. countersunk) screws which seat on a conical face, different types of screw heads can be used interchangeably in the same components. Companies usually use the same kind of screws throughout their product to reduce variety in the inventory and to ease maintenance. Consequently, we assume that the type of head and the type of drive will be predefined by the user.

The geometric conditions that are used for the detection of a threaded fastener joints between any two mating components, are enumerated below.

For "nut & bolt" joints:

- Presence of coaxial holes with equal nominal diameter on the mating faces of the components.
- Possibility of seating the screw-head or nut on the opposite end of both the holes.

For "screw" joints:

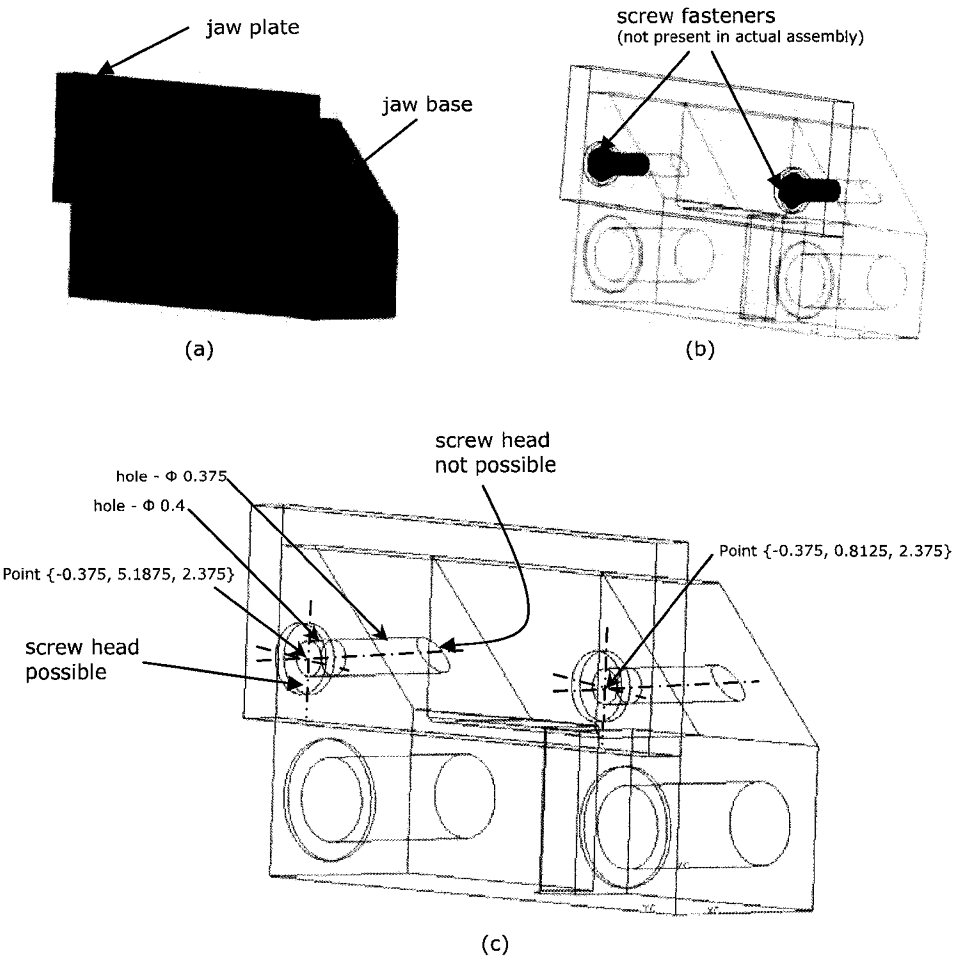
- Presence of coaxial holes on mating faces of the components, such that the nominal diameter of one hole is slightly larger than the other. (The threshold for maximum allowable ratio of diameters is currently set at 1.2).
- Possibility of seating a screw-head on the opposite end of the larger hole.

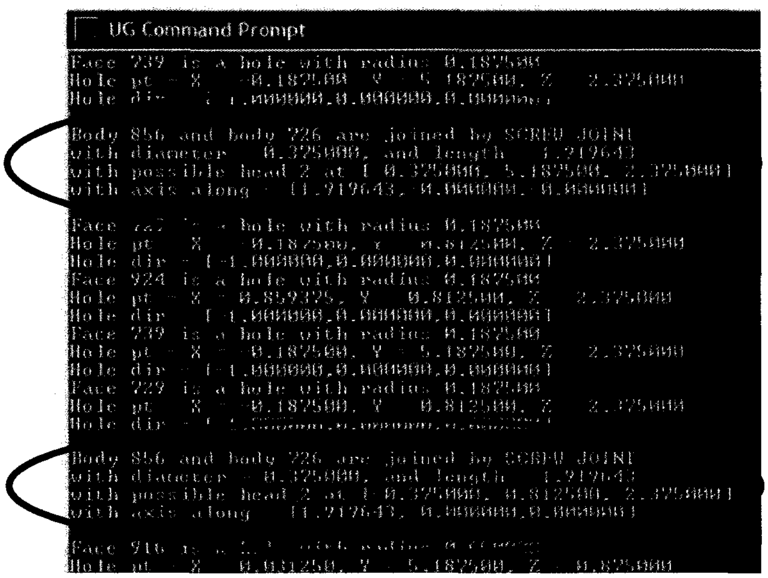
A screw-head can be seated on the end of a hole, if:

- the end is open (as opposed to blind), and
- the through face (adjoining face) for the hole is planar and perpendicular to the hole axis (or conical with standard countersink cone angle and coaxial with hole), and
- the area immediately surrounding the hole (1.5 times the nominal hole diameter) is not obstructed by another component.

The algorithm to identify threaded fastener connections essentially parses the CAD model to search for mating surfaces. If a hole is detected on one of the mating surfaces, it triggers a subroutine to check for conditions of a threaded fastener joint, namely, the existence of a coaxial hole on the opposite mating surface and the possibility of seating a screw-head. The program also infers the exact head location, length of screw/bolt, and orientation of its axis from the geometry of the mating components.

The results of the implementation on a sample part is shown in Figure 4.5. Figure 4.5(a) shows the fixed jaw assembly of a vise clamp. The assembly consists of





```
Face 739 is a hole with radius 0.187500
Hole pt = X = -0.187500 Y = 5.187500, Z = 2.375000
Hole dir = [ 1.000000,0.000000,0.000000]

Body 856 and body 726 are joined by SCREW JOINT
with diameter = 0.375000, and length = 1.919643
with possible head 2 at [ 0.375000, 5.187500, 2.375000]
with axis along = [1.919643, 0.000000, 0.000000]

Face 727 is a hole with radius 0.187500
Hole pt = X = -0.187500, Y = 0.812500, Z = 2.375000
Hole dir = [-1.000000,0.000000,0.000000]
Face 924 is a hole with radius 0.187500
Hole pt = X = 0.859375, Y = 0.812500, Z = 2.375000
Hole dir = [-1.000000,0.000000,0.000000]
Face 739 is a hole with radius 0.187500
Hole pt = X = -0.187500, Y = 5.187500, Z = 2.375000
Hole dir = [-1.000000,0.000000,0.000000]
Face 729 is a hole with radius 0.187500
Hole pt = X = -0.187500, Y = 0.812500, Z = 2.375000
Hole dir = [ [illegible]

Body 856 and body 726 are joined by SCREW JOINT
with diameter = 0.375000, and length = 1.919643
with possible head 2 at [-0.375000, 0.812500, 2.375000]
with axis along = [1.919643, 0.000000,0.000000]

Face 916 is a [illegible] with radius [illegible]
Hole pt = X = 0.031250, Y = 5.187500, Z = 0.875000
```

(d)

Figure 4.5: Case study for identification of threaded fastener joints

only two components, namely, the jaw base and the jaw plate, joint with each other using two hexagonal head screws. The screws are shown in Figure 4.5(b) for purpose of illustration and are not a part of the assembly presented to the program. Figure 4.5(c) shows details of the CAD model and the geometric features that are used to identify presence of the "screw" joints.

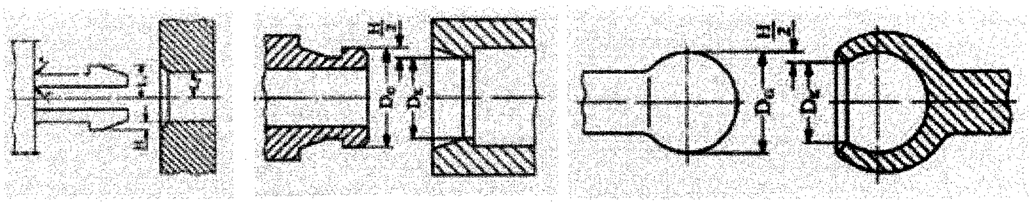
The output of the program is shown in Figure 4.5(d). As can be seen, both "screw" joints were detected. The screw head, in both cases, is located on the jaw plate end with the screw axis oriented in the positive Z-axis direction. The screw head cannot be located on the jaw base, since the through face is not perpendicular to the hole axis. The diameter of the screw is correctly determined. The combined length of the coaxial holes is output as the maximum possible length of the screw.

Other holes (corresponding to guide rails of the vise) are also detected on the mating face of the jaw base, but do not have corresponding coaxial holes on the jaw plate, and are therefore removed from further consideration.

4.5.2 Identification of snap fits

There are three basic types of snap fits [1] usually used in products. (Other methods to classify snap fits, such as annular, cantilever & torsional, have also been discussed in literature but are equivalent for the purposes of this research). They are:

1. "Jaw" or "Barbed leg" type fits (Figure 4.6(a)), which use cantilever deflection for assembly and disassembly.
2. "Cylindrical" snap fits (Figure 4.6(b)), which employ annular deflection of a



(a) (b) (c)

Figure 4.6: Basic types of snap fits [1]

cylindrical jaw or lip for assembly and disassembly.

3. “Spherical” or “Ball and Socket” snap fits (Figure 4.6(c)), which employ deflection of a spherical cup or socket to attach a spherical ball on the mating part.

In addition, various intricate designs have been used to obtain snap fits between components. Although all these joints use similar principles of compliant shapes, the different modified shapes may require fairly different tools and forces to obtain the required deflection to engage and disengage the joint. In this research, we restrict our attention to the basic three types listed above.

“Jaw” type snap fits

Figure 4.7 shows a schematic of the main element, the cantilever jaw, in a “jaw” type snap fit. The jaw at the end of the cantilever beam is made up of a *rise face*, which is pushed against the mating part to cause deflection during assembly, and the *contact face*, which touches the mating part in assembled condition.

For any given pair of mating parts with planar mating surfaces, the conditions for presence of a snap fit are:

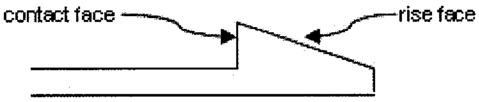


Figure 4.7: Cantilever jaw in snap fits

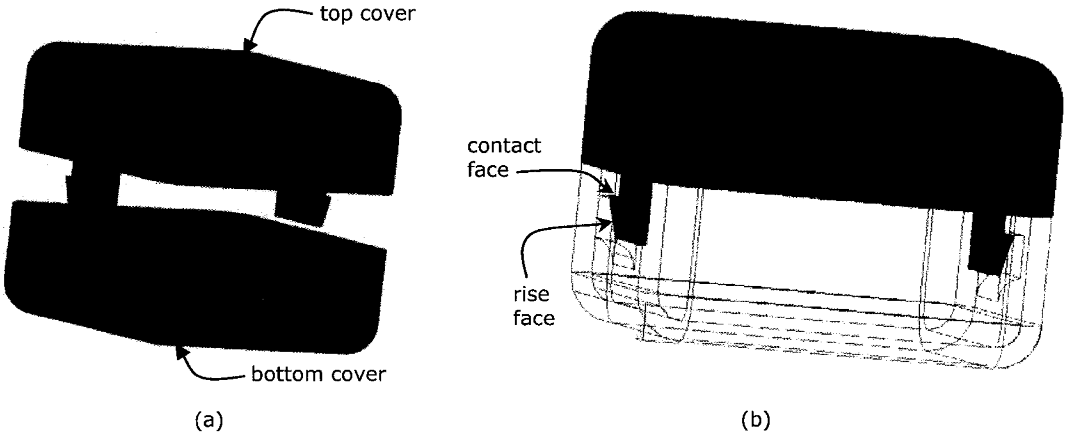
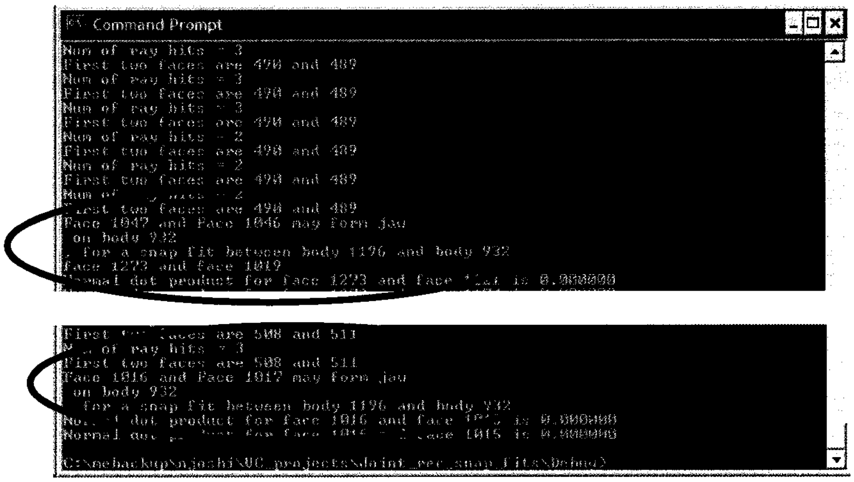


Figure 4.8: Example part with “jaw” type snap-fit

- There must exist a potential rise face, i.e. a slanting face adjoining the mating face, on one of the mating components, and
- The projection of the rise face on the contact face must entirely cover the area of contact between the two mating contact faces.

The algorithm to identify jaw type snap fits parses the assembly model for planar mating surfaces between components. For each planar mating face, the algorithm calculates the normal of each adjoining face. If the normal of the adjoining face makes an obtuse angle with the normal of the original mating face, the algorithm calculates the projection of the adjoining face on the mating face. If the projection of the adjoining face completely covers the mating face, the component is identified as having the jaw for a cantilever jaw type snap fit.



```
Num of ray hits = 3
First two faces are 490 and 489
Num of ray hits = 3
First two faces are 490 and 489
Num of ray hits = 3
First two faces are 490 and 489
Num of ray hits = 2
First two faces are 490 and 489
Num of ray hits = 2
First two faces are 490 and 489
Num of ray hits = 2
First two faces are 490 and 489
Face 1047 and Face 1046 may form jaw
 on body 932
, for a snap fit between body 1196 and body 932
Face 1273 and face 1019
Normal dot product for face 1273 and face 1019 is 0.000000
```

```
First two faces are 508 and 511
Num of ray hits = 3
First two faces are 508 and 511
Face 1016 and Face 1017 may form jaw
 on body 932
 for a snap fit between body 1196 and body 932
Normal dot product for face 1016 and face 1017 is 0.000000
Normal dot product for face 1016 and face 1015 is 0.000000

C:\nebackup\njoshi\UC_projects\Joint_rec_snap_fits\Debug>
```

Figure 4.9: Program output for part with "jaw" type snap-fit

Figure 4.8(a) shows the exploded view of a simplified cover assembly (for a fuse box, or battery unit). It has two parts, namely, the bottom cover and the top cover, which is snap fitted into the bottom cover in the assembled condition. Figure 4.8(b) shows the assembled configuration, as is presented to the program.

As can be seen from the output of the program, Figure 4.9, the program accurately determines the faces on the top cover, which form the jaw for a snap fit. The contact and rise faces are identified. The location and orientation of the joint is given by the location and orientation of the contact and rise faces.

"Cylindrical" snap fits

Cylindrical snap fits are similar to jaw type snap fits. A cylindrical protrusion (henceforth, referred to as the shaft) on one component has an annular jaw that engages in a recessed hole on the other part. Thus, the contact face on the shaft is annular and the rise face is conical, such that the projection along the axis, covers the annular mating face. Figure 4.10(a) shows a hypothetical part with two types

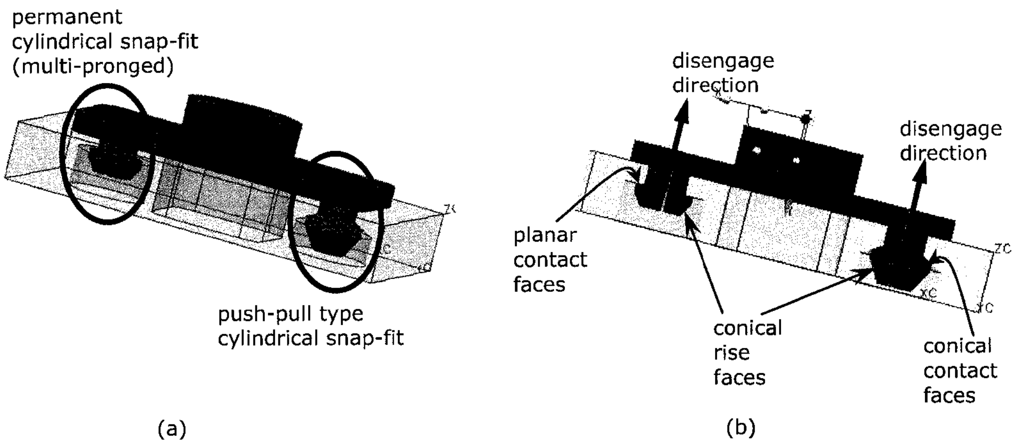
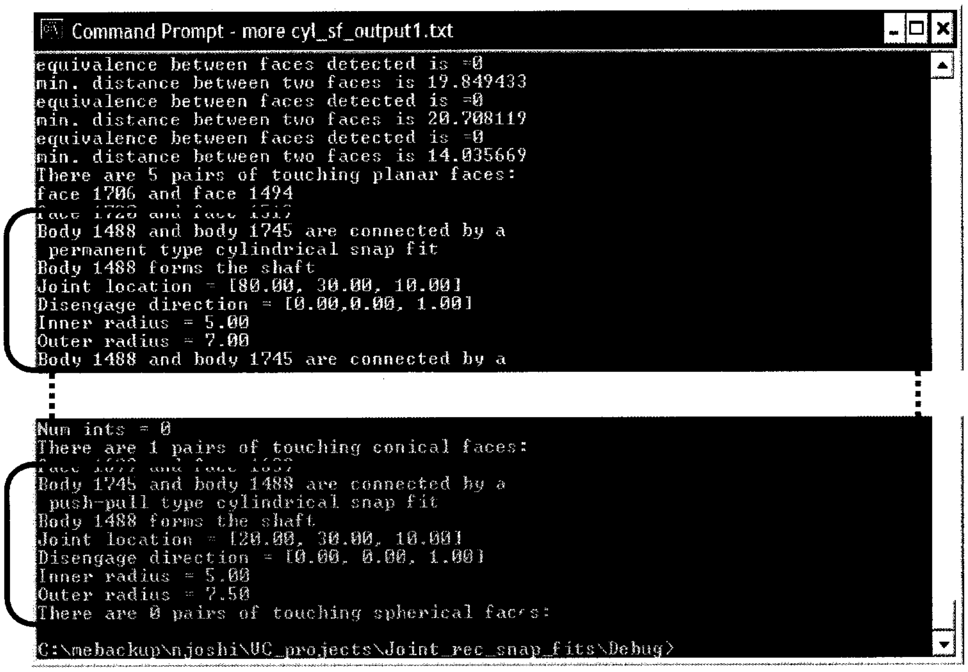


Figure 4.10: Example part with "cylindrical" snap fit

of cylindrical snap fits. If the contact faces on the two components are planar, the joint is referred to as "permanent cylindrical snap fit" since it cannot be disengaged by simply pulling the components apart along the axis of the joint. In such cases, the shaft is usually relieved to form multiple prongs, which can be pressed together on the rise faces to disengage the joint. If the contact faces on the components are conical, such that the joint can be disengaged by pulling the components apart, the fit is referred to as a "push-pull type cylindrical snap fit". The shaft may or may not be relieved. Figure 4.10(b) shows contact faces, rise faces, and the disengage direction for both the cylindrical snap fits in the example part.

The algorithm to find cylindrical snap fits parses the assembly model to search for planar and conical mating faces with an annular area of contact. The program then establishes which of the components in contact can form the shaft in a cylindrical snap fit by analyzing the geometry of the contact faces. Thereafter, the program searches conical faces on the shaft component. If a conical face is found such that its axis passes through the center of the annular contact area and its projection



```
equivalence between faces detected is =0
min. distance between two faces is 19.849433
equivalence between faces detected is =0
min. distance between two faces is 20.708119
equivalence between faces detected is =0
min. distance between two faces is 14.035669
There are 5 pairs of touching planar faces:
face 1706 and face 1494
face 1720 and face 1517
Body 1488 and body 1745 are connected by a
 permanent type cylindrical snap fit
Body 1488 forms the shaft
Joint location = [80.00, 30.00, 10.00]
Disengage direction = [0.00,0.00, 1.00]
Inner radius = 5.00
Outer radius = 7.00
Body 1488 and body 1745 are connected by a
```

```
Num ints = 0
There are 1 pairs of touching conical faces:
face 1677 and face 1637
Body 1745 and body 1488 are connected by a
 push-pull type cylindrical snap fit
Body 1488 forms the shaft
Joint location = [20.00, 30.00, 10.00]
Disengage direction = [0.00, 0.00, 1.00]
Inner radius = 5.00
Outer radius = 7.50
There are 0 pairs of touching spherical fac?s:

C:\mebackup\njoshi\UC_projects\Joint_rec_snap_fits\Debug>
```

Figure 4.11: Program output for part with "cylindrical" snap fits

covers the contact area, it is identified as the rise face. Depending upon whether the contact faces are planar or conical the fit is classified as "permanent" or "push-pull" type. The disengagement direction is opposite to the axis direction of the conical rise face. Figure 4.11 shows the output obtained from the program for the example part shown in Figure 4.10.

"Spherical" or "ball and socket" snap fits

A "spherical" snap fit is obtained when a protrusion with a spherical tip, called ball, on one component mates with a spherical cavity, called socket, on the other component. Figure 4.12(a) shows an example part with "spherical" snap fits. The socket is often formed by multiple faces in order to flex to allow assembly of the joint as also to relative rotation along multiple axes while constraining the translation.

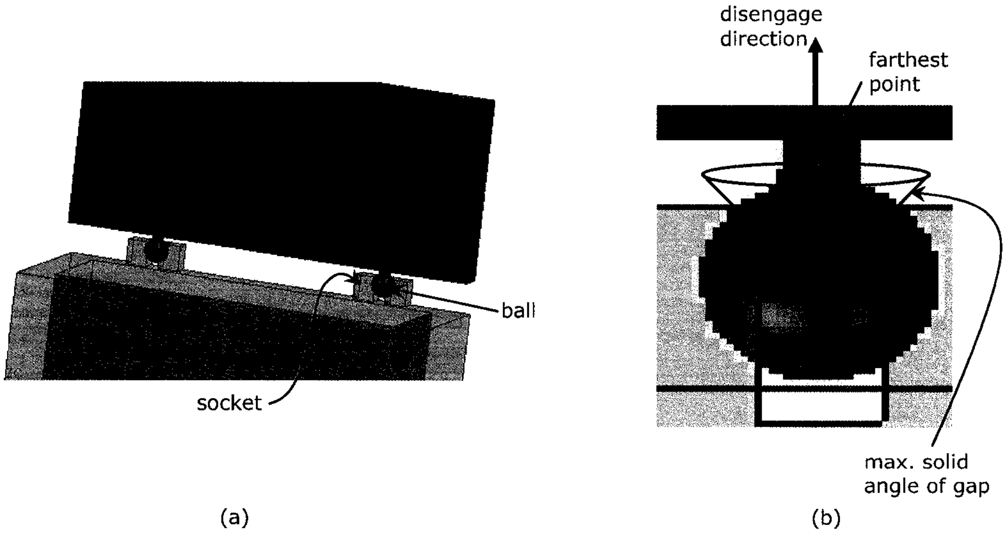
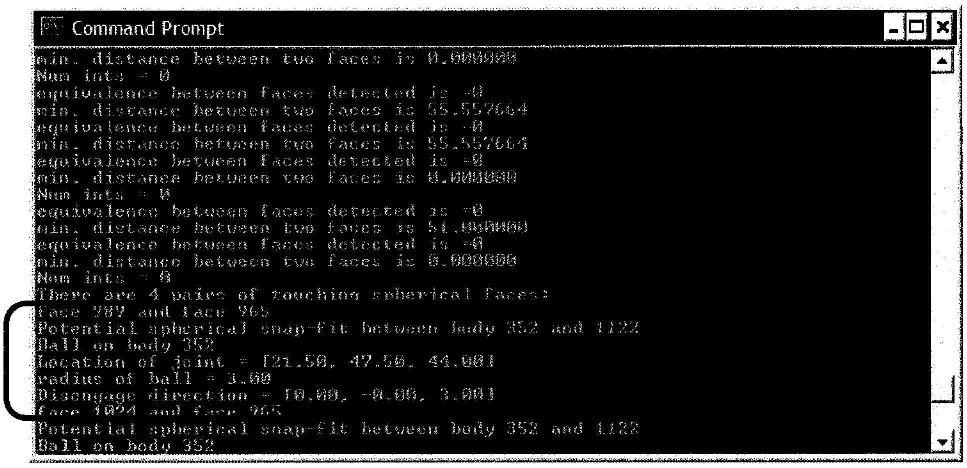


Figure 4.12: Example part with "spherical" snap fit

The algorithm to find spherical snap fits begins by parsing the assembly model for mating spherical faces. The component containing the ball feature is identified using the material side information, and the location and size of the ball is noted. Thereafter, equispaced sample points are created on the surface of the ball and their shortest distance to the faces of the socket component is calculated. If the sample point is covered by a socket face, this distance will be zero. Points that are not covered will have a positive distance from the closest face on the socket. Thus the point that has the maximum shortest distance will be at the center of the largest gap in the socket. Thus the direction of disengagement is identified as the vector from the center of the ball toward this maximum distance point. The minimum cone angle of gap can be calculated using the farthest distance, and can be used to calculate the force required for disengagement. Figure 4.13 shows the output of the program for the example part shown in Figure 4.12.



```
min. distance between two faces is 0.000000
Num ints = 0
equivalence between faces detected is =0
min. distance between two faces is 55.557664
equivalence between faces detected is =0
min. distance between two faces is 55.557664
equivalence between faces detected is =0
min. distance between two faces is 0.000000
Num ints = 0
equivalence between faces detected is =0
min. distance between two faces is 51.000000
equivalence between faces detected is =0
min. distance between two faces is 0.000000
Num ints = 0
There are 4 pairs of touching spherical faces:
face 989 and face 965
Potential spherical snap-fit between body 352 and 1122
Ball on body 352
Location of joint = [21.50, 47.50, 44.00]
radius of ball = 3.00
Disengage direction = [0.00, -0.00, 3.00]
face 1024 and face 965
Potential spherical snap-fit between body 352 and 1122
Ball on body 352
```

Figure 4.13: Program output for part with "spherical" snap fit

4.6 Limitations and Future Work

In this chapter, we have presented a framework for dynamic, case-based selection of the treatment strategy for end-of-life products. To enable integrated use of CAD models as the source of assembly information, we have developed rule-based heuristics to identify and characterize different types of joints, namely threaded fastener joints and snap fits, in CAD assembly models. However, the current implementation stores the information about joints inferred from the CAD models in separate files. Standardized schemas, as discussed in [59], to represent assembly information in CAD models, including detailed information about connections/joints and mating constraints, will be required to store the information inferred directly in the CAD models and maintain associations with the feature parameters.

Algorithms have been presented in this chapter to identify and characterize three common types of snap fits. However, various different shapes and configurations are used to obtain snap fits. Separate heuristics will be required to include other configurations that form snap fits.

Finally, in order to determine the feasibility and cost of removing the joint, one needs to use the joint characteristics inferred to determine tools required for disengagement and accessibility requirements or conditions. This involves determination of a collision free path for the tool to reach the joint, complete the range of motion required to disengage the joint, and return to its original location outside the part along with the joining element, at any given state of disassembly. Clamping and manipulation of parts being separated also needs to be considered. Offline robotic motion planning methods [56], involving use of distance maps, can be used to determine collision free paths for the tool. Such methods have been studied for automated PC disassembly [60] and for removing threaded connections in electronic waste [61]. These methods assume that a single well-defined robotic disassembly station is available for disassembly. To extend the methods to an enterprise-wide framework, as presented in this chapter, formal representations to exchange information the tools and equipment available at the treatment facilities and their capabilities will also be required.

CHAPTER V

Conclusion

This chapter provides a summary of the work described in this thesis. It also highlights the important contributions of this work and discusses directions for future research.

5.1 Research Summary and Contributions

This research has developed methodologies to assist manufacturers in making decisions that have traditionally relied on human experience and expertise. The research identified concerns arising from the introduction of product end-of-life regulations in various stages of the product development cycle.

For the early design phase, we present a methodology to decide material and processing specifications for different components of the product in order to obtain the best performance while proactively accounting for hazardous substance regulations and recyclability requirements. This will reduce chances of late detection of regulatory violations and consequent delays or penalties. The framework also provides a channel for suppliers to provide feedback to OEMs, with respect to feasability and costs of various alternative specifications, and thereby avoid undue pressure to meet unreasonable specifications. A chance constrained programming model is used to account for uncertainty about component properties at the design embodiment stage. A solution methodology has been demonstrated for cases involving "individual chance constraints" as well as "joint chance constraints". The framework, along with the chance constrained model, can be suitably extended to incorporate additional product requirements which cannot be quantified at the early design stages.

Late design and production stages are often hampered by inadequate evaluation of engineering changes. In this research, we have developed a decision support system that dynamically generates a workflow for studying the cascaded effects of a proposed engineering change (EC). Techniques have been developed to find and analyze previous instances of similar changes, to facilitate the evaluation while ensuring that all important effects are identified and studied. The method enables quick and comprehensive review of proposed ECs. It will reduce the time required for evaluating ECs as compared to the "standard track" approval process, while at the same time avoid drawbacks of the "fast track" approval process. In addition, the method will reduce the need for experience and expertise on the part of the users, thereby reducing pressure on important human resources and allowing simultaneous processing of a large number of ECs. The methods used for capture and reuse of knowledge from past ECs may be suitably applied for other applications involving generation and reuse of specialized knowledge and insights (e.g., drug discovery, market analysis and prediction, etc.).

Finally, we have described a framework for case-based selection of the treatment plan for end-of-life products, taking into account available facilities, regulatory requirements, markets for reused and recycled material, condition of incoming products, etc. This will allow OEMs to maintain profitability while at the same time meeting the regulations and achieving the goal of environmental sustainability. In an effort towards integrating this framework with existing CAD and PLM systems, we have developed heuristics to identify different types of joints between components from CAD assembly models. The joints are also characterized with regards to size, location, and orientation, to enable calculation of the feasibility and costs of disengaging the joint. As standardized schemas [59] for capturing information about joints in CAD models are established, these heuristics will also assist in ensuring consistency of the model and maintaining associations between the joint information and geometric feature parameters.

5.2 Future Research

The methods developed in this research are limited in their scope and serve to demonstrate the use of the PLM framework to address the three issues identified in this thesis. Further steps required to broaden the scope of the methods to allow implementation in large scale product manufacturing companies are discussed in sections 2.7, 3.7, and 4.6 respectively.

In addition, we indicate few new and interesting directions for future research that are related to the topics discussed in this thesis:

1. Study of selection of component specifications, while allowing different product configurations: Often different alternative technologies to meet specifications

for the component require different product configurations. Incorporating varying product configurations while deciding component specifications presents an interesting problem.

2. Study of previous engineering changes to suggest design modifications for a given Problem Report: A Problem Report (PR) merely reports a problem in the existing product. The ability to use previously studied PRs or ECRs to suggest design modifications to fix the issue will be extremely useful.

3. Study of previous designs and engineering changes to ascertain impacts of a design decision during new product design: Design decisions during the early stages of new product design are largely dependent on human expertise. The ability to quantify the impacts of a design decision will be very useful.

4. Study of the change in lifecycle environmental impacts of a product for any requested engineering change: Environmental impacts of a product are often quantified using Life Cycle Assessment (LCA) techniques. This process is time consuming and is usually not repeated for the same product. The ability to predict the changes in environmental impacts for any given EC will be extremely useful for updating the LCA assessment, and maintaining accurate information about the environmental performance of the current product.

APPENDIX

APPENDIX A

Constraint equations arising from various product end-of-life regulations

In this appendix, we provide examples of converting regulatory requirements into constraint equations that can be used in the mathematical formulation developed in Chapter II. The goal of this exercise is to explain to the readers the types of constraint equations obtained, and to help readers to develop constraint equations should they wish to implement the method explained in Chapter II for their own product applications.

While developing these equations, we shall consider that the said product configuration has n components $(p_1, p_2, ..., p_n)$, and for each component p_k there are m_k alternatives to choose from. The variable x_{kl} is the binary decision variable that denotes whether p_{kl} (i.e. the l^{th} alternative for the component p_k) is selected. We shall also consider that all random variables defined to represent various properties of the component alternatives are normally distributions with known means and standard deviations.

A.1 Directive 2002/96/EC on waste electrical and electronic equipment (WEEE)

Under WEEE directive [5], for equipment falling under categories 1 and 10 of Annex IA, the required minimum rate of component, material and substance reuse and recycling shall be 75% by an average weight per appliance. That means that at least 75% by weight of the product must be reusable or recyclable.

Let the estimated weight of each component be denoted by the random variable w, such that w_{kl} represents the weight of the p_{kl}. Similarly, let I_{kl} represent the total amount (weight) of recyclable and/or reusable material in p_{kl}. Then, the requirement can be formulated as the following constraint equation;

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k} I_{kl}x_{kl} \geq 0.75\sum_{k=1}^{n}\sum_{l=1}^{m_k} w_{kl}x_{kl} \tag{A.1}$$

The above equation can further be written in the form used in the mathematical formulation in Chapter II, as shown below:

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k} \left(I_{kl} - 0.75w_{kl}\right) x_{kl} \geq 0 \tag{A.2}$$

In addition, for equipment falling under categories 1 and 10 of Annex IA, the required minimum rate of recovery shall be 80% by an average weight per appliance. That means that at least 80% by weight of the product must be recoverable. Let J_{kl} represent the total amount (weight) of recoverable material in p_{kl}. Thus the corresponding constraint equation will be;

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k} \left(J_{kl} - 0.8w_{kl}\right) x_{kl} \geq 0 \tag{A.3}$$

Similarly, the constraint equations for equipment falling under categories 3 and 4 of Annex IA will be;

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k}\left(I_{kl}-0.65w_{kl}\right)x_{kl}\geq 0 \tag{A.4}$$

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k}\left(J_{kl}-0.75w_{kl}\right)x_{kl}\geq 0 \tag{A.5}$$

The constraint equations for equipment falling under categories 2, 5, 6, 7 and 9 of Annex IA will be;

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k}\left(I_{kl}-0.5w_{kl}\right)x_{kl}\geq 0 \tag{A.6}$$

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k}\left(J_{kl}-0.7w_{kl}\right)x_{kl}\geq 0 \tag{A.7}$$

The constraint equations for gas discharge lamps will be;

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k}\left(I_{kl}-0.8w_{kl}\right)x_{kl}\geq 0 \tag{A.8}$$

A.2 Directive 2002/95/EC on restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS)

The RoHS directive [6] allows a maximum concentration value of 0.1% by weight in homogeneous materials for lead, mercury, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE) and of 0.01% weight in homogeneous materials for cadmium.

Let us consider that the components in the product configuration are defined such that each component is made from a single homogeneous material. Let $w\left(Pb\right)_{kl}$ the amount of lead (Pb) in p_{kl} in terms of percentage by weight. Then the restriction can be written as the following constraint;

$$\sum_{l=1}^{m_k} w\left(Pb\right)_{kl} x_{kl} \leq 0.1 \tag{A.9}$$

... for all $k \in$ {Components that are not exempt}

Similar constraint equations can be formulated for other restricted substances too.

N.B. - It should be noted that since these restrictions are applicable directly to a homogeneous material, it simply results in elimination of certain component alternatives. Nonetheless, given the number of different exemptions and special cases, it is beneficial to have constrains that ensure that alternatives that would violate the regulations are automatically eliminated.

Let us consider an example of a special case. For homogeneous materials that have lead as an alloying element the above maximum concentration values are relaxed to allow steel containing up to 0.35% lead by weight, aluminium containing up to 0.4% lead by weight and as a copper alloy containing up to 4% lead by weight.

Let $matl\left(Steel\right)_{kl}$ be a binary variable indicating whether the l^{th} alternative for component p_k is made from a steel alloy. Similarly, let $matl\left(Al\right)_{kl}$ denote whether p_{kl} is an Aluminum alloy, $matl\left(Cu\right)_{kl}$ denote whether it is a Copper alloy. The resulting constraint equation will be of the form;

$$\sum_{l=1}^{m_k} \left\{ \begin{array}{c} \left(w\left(Pb\right)_{kl} - 0.35\right) matl\left(Steel\right)_{kl} + \left(w\left(Pb\right)_{kl} - 0.4\right) matl\left(Al\right)_{kl} + \\ \left(w\left(Pb\right)_{kl} - 4\right) matl\left(Cu\right)_{kl} \end{array} \right\} x_{kl} \leq 0 \tag{A.10}$$

... for all $k \in$ {Components made from metal alloys}

A.3 Directive 2000/53/EC on end-of-life vehicles (ELV)

The ELV directive [4] requires that for all end-of-life vehicles, the reuse and recycling should be a minimum of 80% by an average weight per vehicle. The reuse and recovery for these vehicles should be at least 85%.

Similar to the WEEE directive, these requirements can be translated into the following constraints;

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k}(I_{kl}-0.8w_{kl})\,x_{kl}\geq 0 \tag{A.11}$$

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k}(J_{kl}-0.85w_{kl})\,x_{kl}\geq 0 \tag{A.12}$$

The directive further disallows the use of certain hazardous substances, viz. lead, mercury, cadmium and hexavalent chromium, except in cases listed in Annex II. The constraints resulting from these exemptions will take a form similar to the constraint equations for the RoHS directive.

Let us consider an example of an exemption that different from the RoHS directive. The directive allows a maximum of 2g per vehicle of CrVI to be used for corrosion prevention coatings. Let H_{kl} represent the amount (weight in g) of CrVI contained in the corrosion prevention coating of alternative p_{kl}. Then the constraint equation can be written as;

$$\sum_{k=1}^{n}\sum_{l=1}^{m_k}H_{kl}x_{kl}\leq 2 \tag{A.13}$$

A.4 Regulations relating to restrictions on the use, etc. of certain dangerous chemicals - Laid down by the Ministry of Environment, Norway

Several laws enacted by different countries specify prohibitions and maximum allowable concentration limits for substances similar to those in the RoHS and WEEE directives. The number of substances regulated is usually greater than those specified in the RoHS directive. In this appendix, we shall use the regulations laid down by Norway [62] to indicate a clause that is not similar to the clauses in the RoHS or WEEE directives.

This regulation also prohibits any packaging in which the sum of the concentration levels of lead, cadmium, mercury and hexavalent chromium exceeds 100mg/kg (or 0.01% by mass).

Let w_{kl} represents the weight of component alternative p_{kl}, where p_k is a component in the packaging. Let $w\left(Pb\right)_{kl}$, $w\left(Cd\right)_{kl}$, $w\left(Hg\right)_{kl}$ and $w\left(CrVI\right)_{kl}$ represent the amounts of lead, cadmium, mercury and hexavalent chromium respectively in p_{kl}, in terms of percentage of the total mass of the component. Then the corresponding constraint equation can be written as shown below;

$$\sum_{k\in A}\sum_{l=1}^{m_k}\left[w\left(Pb\right)_{kl}+w\left(Cd\right)_{kl}+w\left(Hg\right)_{kl}+w\left(CrVI\right)_{kl}-0.01\right]w_{kl}x_{kl}\leq 0 \tag{A.14}$$

... where $A = \{$Set of all components in the packaging$\}$

BIBLIOGRAPHY

BIBLIOGRAPHY

[1] *Design calculations for snap fit joints in plastic parts*, 2nd ed., Ticona GmbH, Kelsterbach, 2004.

[2] *PLM Strategy Key to Future Manufacturing Success*, ARC Advisory Group, Dedham, MA, October 2001.

[3] F. Ameri and D. Dutta, "Product Lifecycle Management: Closing the knowledge loops," *Computer-Aided Design and Applications*, vol. 2, no. 5, pp. 577–590, 2005.

[4] *Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles*, Official Journal of the European Communities, Official Journal of the European Communities, October 2000. [Online]. Available: http://europa.eu.int/eur-lex/pri/en/oj/dat/2000/l_269/l_26920001021en00340042.pdf

[5] *Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE)*, Official Journal of the European Union, Official Journal of the European Union, February 2002. [Online]. Available: http://europa.eu.int/eur-lex/pri/en/oj/dat/2003/l_037/l_03720030213en00240038.pdf

[6] *Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment*, Official Journal of the European Union, Official Journal of the European Union, February 2003. [Online]. Available: http://europa.eu.int/eur-lex/pri/en/oj/dat/2003/l_037/l_03720030213en00190023.pdf

[7] S. Skerlos, "Principles of EcoDesign and Manufacturing," Course Notes, University of Michigan College of Engineering, Ann Arbor, MI, Fall 2003.

[8] *Directive 2003/108/EC of the European Parliament and of the Council of 8 December 2003 amending Directive 2002/96/EC on waste electrical and electronic equipment (WEEE)*, Official Journal of the European Union, Official Journal of the European Union, December 2003. [Online]. Available: http://europa.eu.int/eur-lex/pri/en/oj/dat/2003/l_345/l_34520031231en01060107.pdf

[9] N. J. Wavra, "The European Union Directive on Waste from Electrical and Electronic Equipment (WEEE)," Project report for Master of Arts in Commercial Diplomacy Program, Monterey Institute of International Studies, May 2000. [Online]. Available: http://www.commercialdiplomacy.org/pdf/ma_projects/WavraMAP.pdf

[10] *End of Life Vehicles Directive*, PricewaterhouseCoopers, September 2002. [Online]. Available: http://www.pwc.com/extweb/pwcpublications.nsf/4bd5f76b48e282738525662b00739e22/40f04991dc658b0d85256c5500636118/$FILE/End%20of%20Life.pdf

[11] *Proceedings of OECD Seminar on Extended Producer Responsibility: EPR Programme Implementation and Assessment - Part 1: Taking Stock of Operating EPR Programmes.* Organisation for Economic Co-operation and Development, Oct 2003. [Online]. Available: http://www.olis.oecd.org/olis/2003doc.nsf/43bb6130e5e86e5fc12569fa005d004c/a4064d7652f74b37c1256dc80026776c/$FILE/JT00152068.PDF

[12] *About Extended Producer Responsibility*, MDSMap alliance, 2004. [Online]. Available: http://www.mdsmap.com/en/24.asp

[13] G. Pahl and W. Beitz, *Engineering Design - A systematic approach*, 2nd ed., K. M. Wallace, Ed. London, UK: Springer-Verlag, 1996.

[14] G. L. Vairaktarakis, "Optimization tools for design and marketing of new/improved products using the house of quality," *Journal of Operations Management*, vol. 17, no. 6, pp. 645–653, November 1999.

[15] R. Y. K. Fung, J. Tang, P. Y. Tu, and Y. Chen, "Modelling of quality function deployment planning with resource allocation," *Research in Engineering Design*, vol. 14, no. 4, pp. 247–255, November 2003.

[16] N. Kuppuraju, P. Ittimakin, and F. Mistree, "Design through selection: A method that works," *Design Studies*, vol. 6, no. 2, pp. 91–106, 1985.

[17] P. Kall and S. W. Wallace, *Stochastic Programming*, 1st ed. John Wiley and Sons, 1994.

[18] R. Henrion, *Introduction to chance constrained programming*, Web, http://stoprog.org/index.html?SPIntro/intro2ccp.html. [Online]. Available: http://stoprog.org/index.html?SPIntro/intro2ccp.html

[19] A. Prékopa, *Stochastic Programming.* Dordrecht, The Netherlands: Kluwer Academic Publishers, 1995.

[20] A. Prékopa, "Programming under probabilistic constraint and maximising a probability under constraints," RUTCOR (Rutgers Center for Operations Research), Rutgers University, New Brunswick, NJ, Tech. Rep. RRR

35-93, December 1993. [Online]. Available: http://rutcor.rutgers.edu/pub/rrr/reports93/35.ps

[21] P. Beraldi and A. Ruszczynski, "A branch and bound method for stochastic integer problems under probabilistic constraints," *Optimization Methods and Software*, vol. 17, no. 3, pp. 359–382, 2002.

[22] T. Szántai, "A computer code for solution of probabilistic-constrained stochastic programming problems," in *Numerical Techniques for Stochastic Optimization*, ser. Springer series in Computational Mathematics, Y. Ermoliev and R.-B. Wets, Eds. Springer-Verlag, 1988, vol. 10, ch. 10, pp. 229–236.

[23] D. L. Thurston, "Real and Misconceived Limitations to Decision Based Design with Utility Analysis," *Journal of Mechanical Design*, vol. 123, no. 2, pp. 176–182, June 2001.

[24] J. Barzilai, "Deriving weights from pairwise comparison matrices," *Journal of the Operational Research Society*, vol. 48, no. 12, pp. 1226–1232, 1997.

[25] S. Pugh, *Creating Innovative Products Using Total Design*, 1st ed., D. Clausing and R. Andrade, Eds. Addison Wesley Longman, April 1996.

[26] R. K. Jana and M. P. Biswal, "Stochastic simulation-based genetic algorithm for chance constraint programming problems with continuous random variables," *International Journal of Computer Mathematics*, vol. 81, no. 9, pp. 1069–1076, 2004.

[27] E. Segara, R. A. Kramer, and D. B. Taylor, "Stochastic programming analysis of the farm level implications of soil erosion control," *Southern Journal of Agricultural Economics*, vol. 17, pp. 147–154, 1985.

[28] K. K. Ghiya, A. T. Bahil, and W. L. Chapman, "QFD: Validating Robustness," *Quality Engineering*, vol. 11, no. 4, pp. 593–611, June 1999. [Online]. Available: http://qic.asq.org/perl/search.pl?item=12015

[29] L.-C. Tang and P. Paoli, "A spreadsheet-based multiple criteria optimization framework for quality function deployment," *International Journal of Quality & Reliability Management*, vol. 21, no. 3, pp. 329–347, 2004. [Online]. Available: http://www.emeraldinsight.com/Insight/ViewContentServlet?Filename=Published/EmeraldFullTextArticle/Articles/0400210306.html

[30] J. Dupačová, "Stability and sensitivity analysisfor stochastic programming," *Annals of Operations Research*, vol. 27, pp. 115–142, 1990.

[31] R. G. Boznak and A. Decker, *Competitive product development: A quality Approach to Succeeding in the 90's and Beyond.* Milwaukee, WI: ASQC Quality Press/Business One Irwin, 1993.

[32] G. Q. Huang, W. Y. Yee, and K. L. Mak, "Current practice of engineering change management in Hong Kong manufacturing industries," *Journal of Materials Processing Technology*, vol. 139, no. 1-3, pp. 481–487, 2003.

[33] I. C. Wright, "A review of research into engineering change management: Implications for product design," *Design Studies*, vol. 18, no. 1, pp. 33–42, January 1997.

[34] B. G. Dale, "The management of engineering change procedure," *Engineering Management International*, vol. 1, no. 3, pp. 201–208, 1982.

[35] K. Krishnamurthy and K. Law, "Change management for collaborative engineering," in *Computing in Civil Engineeering:Proceedings of the Second Congress held in conjunction with A/E/C Systems*, vol. 2, 1995, pp. 1110–1117.

[36] T.-K. Peng and A. J. C. Trappey, "A step toward STEP-compatible engineering data management: The data models of product structure and engineering changes," *Robotics and Computer-Integrated Manufacturing*, vol. 14, no. 2, pp. 89–109, 1998.

[37] G. Q. Huang and K. L. Mak, "Computer aids for engineering change control," *Journal of Materials Processing Technology*, vol. 76, no. 1-3, pp. 187–191, 1998.

[38] T. A. W. Jarratt, "A model-based approach to support the management of engineering change," Ph.D. dissertation, University of Cambridge (Engineering Department), Cambridge, UK, 2004.

[39] K. Rouibah and K. R. Caskey, "Change management in concurrent engineering from a parameter perspective," *Computers in Industry*, vol. 50, no. 1, pp. 15–34, 2003.

[40] A. Cardone, S. K. Gupta, and M. Karnik, "A survey of shape similarity assessment algorithms for product design and manufacturing applications," *Journal of Computing and Information Science in Engineering*, vol. 3, no. 2, pp. 109–118, June 2003.

[41] J. E. Burge and D. C. Brown, *Design Rationale Types and Tools*, AI in Design Group, Computer Science Department, WPI, http://web.cs.wpi.edu/Research/aidg/DR-Rpt98.html, 1998. [Online]. Available: http://web.cs.wpi.edu/Research/aidg/DR-Rpt98.html

[42] W. Kunz and H. W. J. Rittel, "Issues as Elements of Information Systems," Institut für Gundlagen Der Planung I.A., Universität Stuttgart, Kleperstraße 11, 7000 Stuttgart 1, Germany, Tech. Rep. Technical Report S-78-2, 1970.

[43] J. Conklin and M. L. Begeman, "gIBIS: a hypertext tool for exploratory policy discussion," *ACM Transactions on Information Systems*, vol. 6, no. 4, pp. 303–331, 1988.

[44] L. S. H. de Mello and A. C. Sanderson, "A correct and complete algorithm for the generation of mechanical assembly sequences," *IEEE Transactions on Robotics and Automation*, vol. 7, no. 2, pp. 228–240, April 1991.

[45] A. Desai and A. Mital, "Evaluation of disassemblability to enable design for disassembly in mass production," *International Journal of Industrial Ergonomics*, vol. 32, no. 4, pp. 265–281, 2003.

[46] A. Gungor and S. Gupta, "An evaluation methodology for disassembly process," *Computers and Industrial Engineering*, vol. 33, no. 1-2, pp. 329–332, 1997.

[47] A. Lambert, "Linear programming in disassembly/clustering sequence generation," *Computers and Industrial Engineering*, vol. 36, no. 4, pp. 723–738, 1999.

[48] R. W. Chen, D. Navin-Chandra, and F. Prinz, "Product design for recyclability: A cost benefit analysis model and its application," in *IEEE International Symposium on Electronics and the Environment*, Virginia, 1993.

[49] D. Navin-Chandra, "The recovery problem in product design," *Journal of Engineering Design*, vol. 5, no. 1, pp. 65–86, 1994.

[50] A. Subramani and P. Dewhurst, "Automatic generation of product disassembly sequences," *Annals of the CIRP*, vol. 40, no. 1, p. 115, 1991.

[51] A. Hula, K. Jalali, K. Hamza, S. J. Skerlos, and K. Saitou, "Multi-criteria decision-making for optimisation of product disassembly under multiple situations," *Environmental Science and Technology*, vol. 37, no. 23, pp. 5303–5313, 2003.

[52] B. Bras and J. Emblemsvåg, "The use of activity-based costing, uncertainty and disassembly action cards in demanufacture cost assessments," *Proceedings of the 1995 ASME Design Engineering Technical Conferences*, vol. 82, no. 1, pp. 285–292, 1995.

[53] M. Santochi, G. Dini, and F. Failli, "Computer aided disassembly planning: State of the art and perspectives," *Annals of the CIRP*, vol. 50, no. 2, pp. 507–529, 2002.

[54] J. Mo, Q. Zhang, and R. Gadh, "Virtual disassembly," *International Journal of CAD/CAM*, vol. 2, no. 1, pp. 29–37, 2002.

[55] T. C. Woo and D. Dutta, "Automatic disassembly and total ordering in three dimension," *Journal of Engineering for Industry*, vol. 113, no. 1, pp. 207–213, 1991.

[56] Y. Ting, W. I. Lei, and H. C. Jar, "A path planning algorithm for industrial robots," *Computers and Industrial Engineering*, vol. 42, pp. 299–308, 2002.

[57] V. N. Ranjan, K. Sivasubramanian, and J. E. Fernandez, "Accessibility and ergonomic analysis of assembly product and jig designs," *International Journal of Industrial Ergonomics*, vol. 23, pp. 473–487, 1999.

[58] "PlanetMath: partition lattices." [Online]. Available: http://planetmath.org/encyclopedia/PartitionLattice.html

[59] S. J. Fenves, R. D. Sriram, R. Sudarshan, and F. Wang, "A product information modeling framework for product lifecycle management," in *CDROM Proceedings of PLM'03 International Symposium on Product Lifecycle Management*, Bangalore, India, July 2003.

[60] F. Torres, P. Gill, S. T. Puente, J. Pomares, and R. Arcil, "Automatic pc disassembly for component recovery," *The International Journal of Advanced Manufacturing Technology*, vol. 23, no. 1-2, pp. 39–46, 2004.

[61] M. B.-V. Kuren, "Automated demanufacturing studies in detecting and destroying, threaded connections for processing electronic waste," in *2002 IEEE International Symposium on Electronics and the Environment*, 2002, pp. 295–298.

[62] M. of Environment Norway, *Regulations relating to restrictions on the manufacture, import, export, sale and use of chemicals and other products hazardous to health and the environment (Product Regulations)*, Norwegian Pollution Control Authority, http://www.sft.no/seksjonsartikkel____30217.aspx, 2002, refer Section 3.1. [Online]. Available: http://www.sft.no/seksjonsartikkel____30217.aspx